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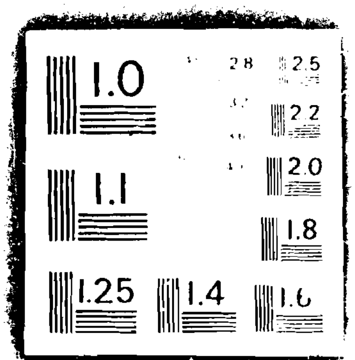

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ADIABATIC SHEAR - AN ANNOTATED BIBLIOGRAPHY

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References relating to the various aspects of Adiabatic Shear have been catergorized into the following general areas: ordnance applications, metalworking, metallurgical studies, and miscellaneous aspects. Adiabatic shear has been recognized as a principal failure mechanism in several technology areas peculiar to the ordnance industry. They are the penetration/perforation of armor, the shatter of kinetic energy projectiles, the fragmentation of steel and the explosive forming of slugs. The workability of a material undergoing adiabatic deformation can either be

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improved due to the formation of a pseudo-superplastic state or degraded due to the localization of strain into narrow bands. Metallurgical studies on metal deformation, ductility, plasticity, and fracture report on the causes and effects of adiabatic shear.

TABLE OF CONTENTS

INTRODUCTION

Adiabatic Shear is a peculiar form of plastic instability that, once established, leads to catastrophic failure. It is peculiar to deformation at high strain rates or cryogenic temperature where the process is "practically" adiabatic.

Many authors have suggested or defined Adiabatic Shear as a thermal-induced plastic instability that is established when the rate of work hardening is overcome by the rate of thermal (deformation) softening. In the light of more recent evidence the authors would suggest the following definition:

Adiabatic Shear: A thermomechanical instability which is established when the rate of strengthening, due to strain hardening and strain rate hardening, is overcome by a combination of the rate of geometrical softening, due to void nucleation and growth, and the rate of thermal softening due to the conversion of mechanical work into thermal energy.

References in this volume relating to the various aspects of Adiabatic Shear have been categorized into the following general areas:

I. Ordnance Applications

II. Metalworking

III. Metallurgical Studies

IV. Miscellaneous Aspects

Adiabatic Shear has been recognized as a principal failure mechanism in several technology areas peculiar to the ordnance industry. They are the penetration/perforation of armor, the shatter of kinetic energy projectiles, the fragmentation of steel and the explosive forming of slugs from plates, cones, etc.

The workability of a material undergoing adiabatic deformation can either be improved due to the formation of a pseudo-superplastic state or degraded due to the localization of strain into narrow bands.

Metallurgical studies on metal deformation, ductility, plasticity, and fracture report on the causes and effects of Adiabatic Shear. Structural changes and phase transformations are also noted.

The sudden release of elastic stored energy, the high hydrostatic pressure, and the poor thermal diffusivity of rock are responsible for the localization of slip and the melting of fault zones during seismic faulting.

Additional evidence of Adiabatic Shear is found in the spallation of hammers.

I. ORDNANCE APPLICATIONS

A. PENETRATION/PERFORATION OF ARMOR

I-A-1. Abbott, K.H., "Effect of Nose Geometry on the Terminal Ballistic Performance of WC Cores," Watertown Arsenal Lab, TR-762/231-8,(December 1953). AD 31 035

A comparison is made between the armor-penetration performance of two truncated conical-nose and one ogival-nosed tungsten carbide cores. The behavior of each type of core during penetration is analyzed. The difficulty of precise mathematical formulation of results is discussed. Several observations of shatter of tungsten carbide cores are made. The correlation between projectile condition and hole type is discussed so that one may be inferred from a visual inspection of the other. All data obtained during the tests are included.

I-A-2. Abbott, K.H., "Metallurgical Observations of High Velocity Impact," Watertown Arsenal Lab, TP 151.85/1, (1960). AD 44 437

Annealed 1020 steel, hardened FXS-318 steel, and 2024-T4 aluminum alloy pellets with length-to-diameter ratios of 1.25 were fired at standard steel armor, aluminum armor, and 301 stainless steel plates at velocities from 2,000 to 13,000 ft/sec. Plate sections containing crater half-sections were subjected to hardness, macrostructure and microstructure measurements to determine metallurgical and phenomena which influence crater formation. Dynamic instabilities resulting in slip with the formation of transformed untempered martensite on maximum shear planes were observed in the standard steel armor. The number of these shear bands with associated cracking increased with increasing pellet velocity. Slip without transformation was observed in both the aluminum alloy and stainless steel plates. No local transformation from austenite to martensite was observed in the stainless steel. Extensive hardening in the vicinity of the crater was measured in all plate materials.

I-A-3. Awerbuch, J., "A Mechanics Approach to Projectile Penetration," <u>Israel Journal of Technology</u> 8:375-383, (1970)

In the program reported in this paper, a mathematical model was developed which describes the mechanism of the normal penetration of metallic targets. The model considers all the forces acting on the projectile during penetration due to the concomittant motion of part of the target mass. With the aid of the mathematical expressions the projectile's velocity after perforation can be calculated by substituting the information on the cavity diameter obtained experimentally. Another part of this program consisted of a series of penetration experiments. For the sake of convenience and from practical considerations, the experimental studies were carried out with .22 caliber lead bullets. The experimental results for the velocity drop due to normal perforation of metallic plates were compared with the mathematical model, and excellent agreement was established. In the frame of this research an explanation for the dependence of the velocity drop on the angle of impact was attempted, and ballistic tests were performed with different materials.

I-A-4. Backman, M. E., "Damage Mechanisms and Terminal Ballistics Research," Transactions of the 6th NWC Warhead Research and Development Symposium, Naval Weapons Center, TP-4835, Vol. 1, p. 111, (October 14-16, 1969). AD 507 165L (Paper unclassified)

Damage mechanisms associated with the ballistic impact of chunky fragments and moderately long fragments against plates or shell structures are identified as: (1) penetration, (2) perforation and secondary internal impacts by the residual projectile, (3) fragmentation and secondary internal impacts by fragments from the perforation process, and (4) auxiliary energy transport and liberation processes associated with perforation fragmentation. Examples are given of the analysis of the operation of conventional fragmenting weapons, shaped charge weapons, and other forms of weapons using controlled fragment distribution in terms of these damage mechanisms. Recent development in terminal ballistic research are discussed with respect to the quantitative analysis of the above-mentioned damage mechanisms. These developments include: (1) the numerical solution of impact problems, (2) the studies of deformation and fracture processes, and (3) studies of very high-velocity ballistics of perforating fragments. The contribution of the item of research to the damage mechanisms is discussed and the outstanding problems in the analysis of the damage mechanism is indicated.

I-A-5. Backman, M. E., "The Dynamics of the Oblique Impact of Projectiles Against Barriers," Transactions of the 7th NWC Warhead Research and Development Symposium, Naval Weapons Center, TP-5295, Vol. 2, p. 291, (November 16-18, 1971). AD 519 986L (Article unclassified)

The dynamics of nondeforming projectiles impacting at obliquity against a barrier is analyzed using current models of penetration resistance and barrier failure. Calculations are carried out for projectile parameters typical of bombs and missiles using empirical representations of resisting force that include the effect of projectile yaw. These are compared to available data on deep penetrations into soils and perforations of finite thickness of metal barriers. The special case of the impact of a sphere against a plate is investigated experimentally and theoretically to focus attention on material response and barrier thickness and thus refine the analysis of resisting force. Prediction of the exit obliquity and final projectile velocity are compared to experimental data for the impact of the hardened steel spheres against mild steel and aluminum alloy barriers. The sudden onset of failures that cause perforation is slow to dominate the deflection of the projectile.

I-A-6. Backman, M. E., and S. A. Finnegan, "Propagation of Adiabatic Shear," Metallugrical Effects at High Strain Rates, edited by R. W. Rohde, pub. by Pelnum Press, p. 531-543, (1973)

Metallographic analysis of metals and alloys subjected to ballistic impact or explosive loading reveals thin bands that are associated with a displacement across the band. Micrographs show examples of these bands found in SAE 4130 to be the result of impact by a steel ball. The shear displacement is shown by the displacement of the surface. These bands occur in regions of general yielding and have been called adiabatic shears because there is evidence that these are inhomogeneous zones of shear in which plastic work heats the zone adiabatically and causes thermal softening within the zone and greatly reduces the shear resistance.

I.A.7. Brunton, J.H., F.E. Field, G.P. Thomas and M.P.W. Wilson, "The Deformation of Metals by High Velocity Impact," Plansee Proceedings p. 137, (1964)

This paper describes a study of liquid/solid and solid/liquid impact for a range of velocities, and the deformation that is produced in metals. When a liquid mass strikes a solid at high velocity, pressures associated with compressible behavior are produced. High-speed photography further shows that the outward flow of liquid after impact may be 2-3 times the impact velocity, depending on the profile of the impacting surface. The deformation process in metals is a combination of the high impact pressures and the shearing action of the flowing liquid. With solids that fail in a brittle fashion, the reflection and interference of stress waves becomes important. Observations of the erosion of solids under repeated liquid impact show that the process is more complex than with single impact, with fatigue now an important failure mechanism in steels. Deformation in the form of localized surface depressions has been observed on metals at pressures an order of magnitude below their yield strengths. No definite correlation appears to exist between the initial erosion rate, and other physical properties such as hardness. In the hypervelocity range, both liquid and solid impact produce similar deformation. An apparatus for firing small solid specimens at velocities up to 5,000 meters/sec. is described. Metallographic observations on metals deformed by hypervelocity impact are discussed.

I-A-8. Carrington, W.E. and M.L.V. Gaylier, "The Use of Flat-Ended Projectiles for Determining Dynamic Yield Stress. Part III - Changes in Microstructure Caused by Deformation under Impact at High-Striking Velocities," Royal Society London Proc 194A:323, (1948)

The mechanism of deformation of metals at high velocities has been studied by examining the microstructure of cylinders of mild steel, duraluminum and standard silver (of composition Ag 92.5%, Cu 7.5%) of similar hardness, and of steel balls after impact on steel plates at velocities from 300 to 3830 ft/sec. The means by which the stress on impact was relieved depended on the material, and was first the formation of twins or "compression bands," i.e., by block movement of wedges of material within individual grains, or by cracking. When the applied stress could no longer be relieved in this way, plastic deformation occurred. The amount of residual strain in deformed mild steel and duraluminum has been examined observing changes of microstructure after annealing. Hardness surveys were made on longitudinal sections of the cylinders and the results correlated with the microstructures and with observations of the limits of strain due to impact.

I-A-9. Craig, J.V., and T.A.C. Stock, "Microstructural Damage Adjacent to Bullet Holes in 70-30-Brass," Australian Institute of Metals Journal 15:1, (1970)

Severely deformed surface layers and bands of intense shear are associated with the bullet holes. Surface layers of similar depth and disposition are associated with slowly punched holes consists of small cells or grains (0.2 gain dia.); there is considerable misorientation between the grains and these are distinctive cell or grain boundaries. On the other hand, the structure of the deformed layers associated with slowly punched holes consists of tangles of dislocations and extinction contours; although there is no distinct cell structure visible, selected area diffraction indicates that many small subgrains or cells are present. It is concluded that polygonization of this type of structure has produced the structures associated with the bullet holes, the necessary heat being generated during adiabatic shear.

I-A-10. Curtis, C.W., "Perforation Limits for Nondeforming Projectiles," Frankford Arsenal, R-903, (February 1951) AD 96 123.

I-A-11. Curtis, C.W., "The Problem of Armor Piercing Projectile Design: Its Principal Division and Important Phases," Frankford Arsenal, R-901, (February 1951) ATI 96 122.

I-A-12. Finnegan, Stephen A., "Metallographic Studies of Inhomogeneous Plastic Deformation in Steel and Titanium Alloy Plates After Ballistic Impact," Transactions of the 6th NWC Warhead Research and Development Symposium, Naval Weapons Center, TP-4835, Vol. 2, p. 463, (October 14-16, 1969) AD 507 165L (Paper unclassified)

Inhomogeneous deformations of two kinds are found in ballistically impacted metals. These include (1) simple shear zones of intense deformation, and (2) modified shear zones showing significant microstructural changes. In the present investigation, SAE 4130 steel and Ti-6Al-4V titanium alloy plates were impacted by SAE 1020 steel spheres at velocities below 6,000 ft/sec. and then examined by standard metallographic techniques to identify the microstructure of the shear zones. Binary phase diagrams, TTT curves and theories of thermoplasticity estimate the possibility of microstructural changes. Simple and modified shear zones were found in both alloys, with the modified zones being characteristic of martensitic microstructures. In the steel, microhardness tests and the response of the zone to heat treatment indicates a martensitic microstructure but other aspects of zone morphology did not. Thus, tentatively, the modified zones are identified as untempered martensite, but other exotic microstructures are not ruled out.

I-A-13. Goldsmith, W.; S.A. Finnegan, and K.I. Rinehart, "Mechanical and Metallographic Studies of Penetration and Perforation Processes in Steel and Aluminum," Transactions of the 7th NWC Warhead Research and Development Symposium, Naval Weapons Center, TP-5295, Vol. 2, p. 447-474, (November 16-18, 1971). AD 519 986L (Paper unclassified)

A mild and an alloy steel as well as two grades of aluminum were subjected to normal impact by hard-steel spheres of various diameters at velocities ranging from 500 to 8,000 ft/sec. A pictorial history of the penetration or perforation process was obtained by means of either a high-speed framing or a Kerr cell camera that permitted a delineation of the contact force variation. Radial and circumferential strain histories were determined at various positions from the impact point. In addition, crater and fragment dimensions were ascertained and supplemented by metallographic examination of the impact region of the targets. The data indicate a diminution in the velocity drop of the projectile just above the ballistic limit followed by a monotonous increase in this parameter with further increase of the bullet speed. The metamorphosis of the perforation mechanism from a bending to a punching in thin plates mode was substantiated both from terminal target configuration and strain gage measurements. Good correlation of the experimental results was obtained with the predictions of a theoretical model encompassing target compression, shear and inertial resistance in a velocity regime considerably above the ballistic limit.

I-A-14. Hayes, G. A., "Development of a Single Element, 20mm, General Purpose Projectile Penetrator (U)," Naval Weapons Center, TP-4617, (February 1969). AD 501 643L (Confidential)

This report describes an experimental testing program to develop an improved penetrator material and design for incorporation in a 20mm general purpose (GP) round. Over 1200 penetration firings were made investigating 27 different penetrator geometrical configurations and 13 materials. The experimental test program consisted of the penetration study, a study of behind-armor effects, and a correlation of the mechanical properties and metallurgical structure of armor and penetrators with achievable penetration. The following experimental variables were investigated: (1) penetrator velocity, (2) penetrator geometry and material, (3) target material, (4) target thickness and hardness, and (5) target angle of obliquity. (U)

I-A-15. Hehemann, R. F. and J. G. Kerr, "Armor-Piercing Steel Projectiles Mechanical Properties," Frankford Arsenal, R-910, (September 1958) AD 225 181

Mechanical properties of steels (particularly those of armor-piercing projectiles) and the principal mechanical tests (tension, compression, and indentation hardness) which measure the resistance of these steels to plastic deformation, are discussed. The relationships between projectile dynamic impact behavior and mechanical properties are shown in terms of correlations with hardness, metallurgical history, and compression tests. In the discussion of various bend and impact tests, projectile body failure is shown to be related to bend strength and metallurgical history. The relationships between projectile shatter and adiabatic shear deformation are shown, and the influence of strain hardening characteristics of steels (determined in compression) upon adiabatic shear behavior is indicated.

I-A-16. Ipson, T. W., and R. F. Recht, "Multiple Plate Perforation," Transactions of the 6th NWC Warhead Research and Development Symposium, Naval Weapons Center, TP-4835, Vol. 2, p. 427, (October 14-16, 1969). AD 507 165L (Paper unclassified)

During ballistic perforation, two distinct fragment mass loss modes are observed. When the deformation mass loss mode is operative, compressive impact pressures produce lateral extrusion of projectile material near the interface, a portion of which is sheared off during subsequent plate perforation. Above a critical velocity, projectile orientations which produce "flat" impacts cause projectile shatter due to shock interactions. The deformation mass loss mode continues to apply above the critical velocity to "non-flat" impacts. DRI and THOR residual velocity and residual mass relations are used to develop multiple plate perforation prediction models. Predictions are compared with data generated at BRL, RARDE, and DRI. In addition to separate residual mass and residual velocity comparisons, residual lethality comparisons are made using the magnitude of the lethality vector $L = M^{c2} V$. Two fragments having the same value of this quantity have nearly equivalent kill and plate perforation capabilities.

I-A-17. Irwin, G. J., "Metallographic Interpretation of Impacted Ogive Penetrators," Defense Research Establishment, Canada, DREV-R-652/72, (October 1972) AD 907 367

A metallographic study was carried out on uranium-based and tungsten-based penetrators which had impacted a semi-infinite soft steel target at normal incidence. The uranium alloys show a great tendency to shear adiabatically at the surface. This is believed to be a function of: (a) low work-hardening capability, (b) severe stress concentration at the abrupt change in penetrator cross section produced during impact deformation, and (3) bending as a secondary influence. Adiabatic shear bands are also a site for ductile fracture. Martensitic U-2Mo is mechanically highly unstable, while U-1Mo-.7Nb-.7Zr, in the lamellar condition shows promise as a potential alternative to W-Ni-Cu at impact velocities above 0.76 mm/μs. The uranium alloy must be sufficiently hard, however, to avoid significant mushrooming.

I-A-18. Manganello, S. J., and K. H. Abbott, "Metallurgical Factors Affecting the Ballistic Behavior of Steel Targets," Journal of Materials 7:231-239, (June 1972)

This paper discusses the effects of material parameters and material processing techniques on ballistic performance against armor piercing projectiles. Various metallurgical and mechanical observations associated with ballistic penetration are described. Specifically, the effects of target composition, microstructure, purity (cleanliness), hardness, ductility, toughness, and surface condition on ballistic behavior are discussed, and relations between some of these parameters and melting and solidification practices, rolling procedures, plate thickness, and heat treatment are given. Variables affecting the resistance of bonded laminar-steel composite targets to ballistic penetration are presented. Projectile fracture, target spalling and cracking, and white streaks (or shear bands) in targets are described.

I-A-19. Minnich, H. R., and N. Davids, "Plug Formation in Plates," Pennsylvania State University, (September 1964) AD 452 043

Both elastic deformation theory and hydrodynamic theory of deformation due to hypervelocity impact are two extremes which leave a gap in the difficult intermediate state where the target material undergoes a type of viscous or plastic deformation. The reason for this gap is the uncertainity in the constants of the material and complexity of the analysis. A very important parameter is the "impact yield strength" below which the material may be assumed quasi-rigid and above which viscous shear flow tends to take place. This type of flow behavior is reasonably accurate for many metals. This work (a) solves the projectile-plate dynamical problem with one-dimensional viscous shear flow of the material taking place above the impact yield constant, and (b) compares the results with the etched specimens made from sections of target plates deformed by firings of almost-flat projectiles. The velocity, vertical shear stress and displacement profiles which are obtained from the calculations are matched against the experimental profiles and enable the impact yield constant to be determined. For armor steel, this is 2.1×10^5 psi, a value considerably higher than conventional static yield values. The coefficient of viscosity is found to be 5.7 lb-sec/in^2. The relationship between plate thickness and total deformation of the plate for a standard impact is determined. The impact is assumed initially uniformly distributed over a circular area of the plate surface, and its variation with time is determined. The significance of the investigation lies in showing probable ranges of material constants in the shear flow regime.

I-A-20. Murr, L. E., and J. V. Foltz, "A Terminal Ballistics Application of Transmission Electron Microscopy: The Anatomy of a Bullet Hole," J Materials Science 5:63-81, (January 1970)

A novel technique was devised for the selected area observation of residual microstructures in the deformation zones and the detached cap sections of .22 caliber bullet holes in thin sheets and laminate thicknesses ranging from 0.03 to 0.54 mm of 304 stainless steel and Inconel 600 by bright-and dark-field transmission electron microscopy. Microhardness measurements over the detached cap and petals, extending radially into the undeformed material, indicated the zone of action to be confined to a region bounded by the deviation of the impact zone from the plane of the plate. This feature was confirmed by electron microscope observations which indicated no defects beyond the bounds of the zone of action so defined. Residual microhardness was observed to increase from the radial bound of the zone of action toward the axis of projectile motion, with mazimum hardness values roughly twice the undeformed sheet hardness observed in the petal edges and the detached caps. Dislocation densities were observed to increase correspondingly over this range (10^6 to 10^{11} cm^{-2}), with deformation twins occurring in the petal edges and the detached caps of both materials. An analytical treatment of the specific ballistic perforation examined in this investigation based on the plastic stretching of the target zone of action, fractu. and detachment of a cap, and the subsequent petalling of the crater as per .ation commences, indicated an absence of high-pressure shock effects.

I-A-21 Recht, R. F., "Containing Ballistic Fragments," 3rd International Conference on High Pressure, (May 1970)

A description of the dangers represented by the fragment hazard is followed by specific definitions concerning the ranges of fragment size, shape, and velocity to be expected. Ballistic limit velocity is that velocity at which a given fragment has an even chance of perforating a plate or other impacted item. It is a function of (1) fragment size, shape, and material, (2) the configuration of the impacted item and the materials of which it is made, and (3) impact orientation. If the impacting velocity is above the ballistic limit velocity, the fragment will ususally perforate the impact item, retaining a residual velocity. If the velocity is below the limit velocity a ricochet will usually occur. Empirical and verified analytical models defining the dynamics of plate perforation and ricochet are used to develop and evaluate shielding criteria. Effects of the total momentum and kinetic energy of a fragment population area considered. Several shielding concepts are reviewed.

I-A-22. Recht, R. F. and J. A. Dunn, "Ballistic Perforation of Spaced Steel Plates by Steel Cubes," Denver Research Institute, DRI-2466, (August 15, 1968)

Steel cubes were fired through single and dual-spaced steel plates at normal obliquity to establish the sensitivity of projectile fracture and post-perforation dynamics to plate spacing and impact orientation. Time-of-arrival switches, orthogonal flash radiographs, and a recovery target were utilized to provide the data necessary to establish weights, trajectories, velocities, and penetration capabilities of all recovered projectile fragments and plate particles weighing over 1/2 grain. Trajectories and certain velocities were measured redundantly to verify the precision of the experiment. Projectile fracture and, thus, post-perforation dynamics are strongly dependent upon impact orientation. Effects of spacing are less pronounced. Appended are the results of an experiment involving ballistic perforation of thin aluminum plates by cylinders.

I-A-23. Recht, R. F., E. S. Grubin, and T. W. Ipson, "The Application of Ballistic Perforation Mechanics to Target Vulnerability and Weapons Effectiveness Analysis (U)," Naval Weapons Center, TP-4532, (December 1, 1967) AD 390 880L (Confidential)

I-A-24. Recht, R. F., E. S. Grubin, D. C. Tucker, and T. W. Ipson, "Vulnerable Area Analysis of a Representative Foreign Fire Control Radar Subjected to Attack by 0.50 Caliber Armor Piercing Projectiles (U)," Naval Ordnance Test Station, TP-4278, (December 30, 1966). AD 380 092L (Confidential)

I-A-25. Recht, R. F., and T. W. Ipson, "Ballistic Perforation Dynamics," Journal of Applied Mechanics 30:384, (No. 3, 1963)

Analytical equations of the types required to define ballistic perforation dynamics are developed. These equations concern both blunt and sharp-nosed fragments, perforating plates normally and at oblique impact angles. Residual velocities are defined in terms of magnitude and direction. Analytical models and confirming experimental data, which are presented here, specifically concern the ballistic velocity impact range to about 25% of the velocity of longitudinal sonic waves in the impacting materials.

I-A-26. Recht, R. F., and T. W. Ipson, "Transformation of Terminal Ballistic Threat Definitions into Vital Component Malfunction Predictions," Naval Weapons Center, TP-4871, (May 1, 1969). AD 867 454L

I-A-27. Sawyer, R. B., "Mechanism of Armor Penetration," Lehigh University, (February 1951). ATI 95 121

The various ways in which a plate may fail when subjected to projectile impact differ both in the controlling factors and in the accompanying physical processes. By sorting out the different modes of failure and treating them individually, the general problem has been considerably simplified. It appears at the present time that the principal types of failure have been identified. Furthermore, very reasonable mechanisms to account for these types have been proposed, so there exists a good qualitative picture of the perforation process. This picture serves the useful purpose of indicating the most important factors controlling perforation and of providing a basis for correlating experimental results. It has not, however, been developed in sufficient detail to permit exact calculations of all the quantities of practical interest to the designer. The mechanisms considered in the present chapter are concerned with the behavior of homogeneous armor when the projectile does not deform. Discussion is confined mainly to the case of normal impact.

1-A-28. Stock, T.A.C., and K.R.L. Thompson, "Penetration of Aluminum Alloys by Projectiles," Metallurgical Trans 1:219, (1970)

Bands of intense shear may be formed during the penetration of aluminum alloys by projectiles. It is shown that the formation of these bands lowers the ability of the material to withstand further projectile penetration. The structure of these bands has been investigated by electron microscopy, and the results obtained indicate that melting occurs within the bands. A simple model of a propagating shear band predicts that the material within the band will melt.

1-A-29. Thompson, K.R.L., T.A.C. Stock, and B.H. McConnoll, "Evidence for Melting of a Low-Melting-Point Alloy During High-Velocity Impact," Journal of the Australian Institute of Metals 51:26, (No. 1, 1970)

The topography of solidified solder surfaces has been investigated using electron microscopy. It is shown that "ripples" which sometimes form on the surface are caused by the presence of an oxide film. Similar ripples were observed on the walls of a crater produced by high-velocity impact. It was concluded that localized melting of the target had occurred during impact.

1-A-30. Williams, T., "Metallization Aspects of the Response of 1-inch Thick Armor Plate Steels to the Attack by Two Types of Tungsten Carbide (U)," Royal Armament Research & Development Est, RM-18/70, (July 1970). Ad 510 727 (Confidential)

Homogeneous steel armor plate heat treated to different strength levels was attacked by small (0.34-in. diam.) conical-headed and spherical (1.25-in. diam.) projectiles to obtain information concerning the effects of high- and low-velocity attack, respectively. Defected plates revealed that the smaller projectiles penetrated by plastic deformation and flow whereas the spherical projectiles caused failure to occur by a shear mechanism. When deformation occurred by plastic flow, the critical velocities showed better agreement with the 0.2% proof stresses of the plates than with their hardness. With spherical projectiles, a linear relationship was established between the critical velocity and the total shear energy obtained in torsion impact testing. It was calculated that the energy dissipated by frictional heating during the passage of conical-headed projectiles through the plate was only about 2% of that dissipated by plastic penetration. (U).

I-A-31. Wingrove, A.L., "Influence of Projectile Geometry on Adiabatic Shear and Target Failure," Metallurgical Trans 4:1829-1833, (August 1973)

An examination has been carried out of the ability of projectiles of three different geometries to perforate plates of an age-hardened aluminum alloy. It was found that flat-ended projectiles perforate the target with greater ease than projectiles with more rounded ends.

The results are discussed in terms of the ability of a particular projectile geometry to promote adiabatic shear during penetration and the mode of fracture when projectile breakout occurs.

I-A-32. Zener, C., and R. E. Peterson, "Mechanism of Armor Penetration," Watertown Arsenal, R-710/492, (May 31, 1943). ATI 38 7·9

The forces which act upon projectiles during armor penetration, and the effects thereof, are investigated. Friction has been found to have a negligible effect during armor penetration. The effect of obliquity upon the ballistic limit is adequately accounted for merely by considering the increase in length of projectile path through the plate. As to the effect of transverse forces on cones of standard caliber .50 AP ammunition, large surface tensile stresses are brought about. These stresses result in fracture of caliber .50 AP cones when fired at obliquities of 20 degrees or over against production plate.

B. SHATTER OF KINETIC ENERGY PENETRATORS

I-B-1. Abbott, K. H., "Effect of Caps on Terminal Ballistic Performance of WC Cores," Watertown Arsenal Lab, TR-762/231-9, (January 1954). AD 30 416

The effects of steel and tungsten caps on the penetration of rolled homogeneous armor by scale-model tungsten-carbide-cored projectiles were studied. Comparisons of the terminal ballistic performance of capped and uncapped cores are given. Discussions of the effect of the cap in reducing core shatter, and the resultant effect on the mechanism of penetration of the armor are included. A presentation designed to illustrate the importance of the cap weight is given.

I-B-2. Abbott, K. H., "Effect of Nose Geometry on the Terminal Ballistic Performance of WC Cores, "Watertown Arsenal Lab, TR-762/231-8, (December 1953). AD 31 035

A comparison is made between the armor penetration performance of two truncated conical-nosed and one ogival-nosed tungsten carbide cores. The behavior of each type of core during penetration is analyzed. The difficulty of precise mathematical formulation of results is discussed. Several observations of shatter of tungsten carbide cores are made. The correlation between projectile condition and hole type is discussed so that one may be inferred from a visual inspection of the other. All data obtained during the tests are included.

I-B-3. Armiento, D. F., H. W. Euker, and T. A. Read, "A Comparison of Five Armor Piercing Core Steels," Frankford Arsenal, R-672, (November 1945)

I-B-4. Curtis, C. W., "The Problem of Armor Piercing Projectile Design; Its Principal Divisions and Important Phases," Frankford Arsenal, R-901, (February 1951). ATI 96 122

Topics covered are the problem of AP projectile design, mechanism of armor penetration, perforation limits for nondeforming projectiles, mechanism of projectile deformation, occurrence of projectile deformation and its effect on limit energy, dependence of deformation on projectile parameters, theory of cap action, attack of homogeneous armor, attack of nonhomogeneous targets, and mechanical properties.

I-B-5. Euker, H. W., and T. A. Read, "The Shatter of Caliber .60 AP Bullets," Frankford Arsenal, R-553, (October 1944)

I-B-6. Euker, H. W. and T. A. Read, "Shatter of Brine Quenched and Air Quenched Caliber .60 FXS 318 Steel Cores," Frankford Arsenal, R-616, (April 1945)

I-B-7. Hehemann, R. F. and J. G. Kerr, "Armor-Piercing Steel Projectiles Mechanical Properties," Frankford Arsenal, R-910, (September 1958). AD 225 181

Mechanical properties of steels (particularly those of armor-piercing projectiles) and the principal mechanical tests (tension, compression, and indentation hardness) which measure the resistance of these steels to plastic deformation, are discussed. The relationships between projectile dynamic impact behavior and mechanical properties are shown in terms of correlation with hardness, metallurgical history, and compression tests. In the discussion of various bend and impact tests, projectile body failure is shown to be related to bend strength and metallurgical history. The relationships between projectile shatter and adiabatic shear deformation are shown, and the influence of strain hardening characteristics of steels (determined in compression) upon adiabatic shear behavior is indicated.

I-B-8. Ipson, T. W. and R. F. Recht, "Multiple Plate Perforation," Transactions of the 6th NWC Warhead Research and Development Symposium, Naval Weapons Center, TP-4835, Vol. 2, p. 427, (October 14-16, 1969). AD 507 165L (Paper unclassified)

During ballistic perforation, two distinct fragment mass loss modes are observed. When the deformation mass loss mode is operative, compressive impact pressures produce lateral extrusion of projectile material near the interface, a portion of which is sheared off during subsequent plate performation. Above a critical velocity, projectile orientations which produce "flat" impacts cause projectile shatter due to shock interactions. The deformation mass loss mode continues to apply above the critical velocity to "non-flat" impacts. DRI and THOR residual velocity and residual mass relations are used to develop multiple plate perforation prediction models. Predictions are compared with data generated at BRL, RARDE, and DRI. In addition to separate residual mass and residual velocity comparisons, residual lethality comparisons are made using the magnitude of the lethality vector $L = M_p^{c2}\ V$. Two fragments having the same value of this quantity have nearly equivalent kill and plate performance capabilities.

I-B-9. Irwin, G. J., "Metallographic Interpretation of Impacted Ogive Penetrators," Defense Research Establishment, Canada, DREV-R-652/72 (October 1972). AD 907 367

A metallographic study was carried out on uranium-based and tungsten-based penetrators which had impacted a semi-infinite soft steel target at normal incidence. The uranium alloys show a great tendency to shear adiabatically at the surface. This is believed to be a function of (a) low work-hardening capability, (b) severe stress concentration at the abrupt change in penetrator cross section produced during impact deformation, and (c) bending as a secondary influence. Adiabatic shear bands are also a site for ductile fracture. Martensitic U-2Mo is mechanically highly unstable while U-1Mo-.7Nb-.7Zr, in the lamellar condition shows promise as a potential alternative to W-Ni-Cu at impact velocities above 0.76 mm/μs. The uranium alloy must be sufficiently hard, however, to avoid significant mushrooming.

I-B-10. McCaughey, J. M. and M. A. Dragoo, "High Speed Compression Tests of Projectile Steels," Frankford Arsenal, R-798, (May 1947). AD 493 311

A method whereby stress-strain data for adiabatic deformation may be obtained by the use of a drop-weight apparatus is described. An adiabatic stress-strain curve is presented for one lot of hardened manganese-molybdenum core steel. The stress-strain relation for adiabatic deformation is extremely important because it is probable that the phenomenon of shatter failure results essentially from the instability of adiabatic deformation of the shot during penetration.

I-B-11. McKean, R. H. and H. W. Euker, "Metallurgical Study of Shattered AP Shot," Frankford Arsenal, R-811, (June 1947)

I-B-12. Zener, C., "Mechanism of Armor Penetration," Watertown Arsenal Lab, R-710/492-1, (March 1944)

I-B-13. Zener, C., "Micro-Mechanism of Fracture," Fracturing of Metals, pub. by American Society for Metals, p. 3-31, (1948)

I-B-14. Zener, C., and J. F. Sullivan, "Principles of Armor Protection," Watertown Arsenal Lab, R-710/607-3, (June 1944). AD 102 333

Irrespective of hardness of cap, closeness of fitting, or of cap design, 1/12 caliber plates remove the caps of APC projectiles at service velocities. The use of such a decapping plate would result in marked lowering of the shatter velocity of the enemy's projectiles, and therefore in their effectiveness, particularly in the important obliquity range of 30 to 45 degrees.

C. EXPLOSIVE FRAGMENTATION

I-C-1. Bedford, A. J., "An Appraisal of a Method of Studying the Early Stages of Natural Fragmentation," Australian Defense Standards Labs, TN-294, (March 1973). AD 912 239

Quick-stop experiments on internally explosvely loaded steel cylinders are performed using larger concentric steel cylinders to halt the expansion. It is shown that excessive amounts of adiabatic shear are induced in the cylinder walls and that this is not characteristic of a natural fragmentation trial.

I-C-2. Bedford, A.J., "The Natural Fragmentation of Steel Cylinders with Tempered Martensite Microstructures," Australian Defense Standards Labs, R-532, (December 1972). AD 912 311

Small steel cylinders with martensitic microstructures produced by heat treating steels of three different carbon contents were explosively fragmented. Some effects of material properties on the fragmentation behavior are assessed by correlating recovered fragment mass distributions with observations made on the operative fracture modes. The fracture modes are determined from optical microscopy of fragment cross sections and from scanning electron microscopy of fracture surfaces. It is shown, for the cylinder sizes used, that coarse fragmentation is associated with predominant ductile shear fracture whereas increases in the contributions from radial tensile fracture and adiabatic shear fracture lead to finer fragmentation. The relationships between the modes of fracture and martensite compositions and heat treatment are discussed, and particular reference is made to the fractography of adiabatically sheared surfaces.

I-C-3. Beetle, James C., and William B. Steward, "A Fractographic Investigation of Explosively Fragmented Silicon-Manganese Steels by Scanning Electron Microscopy," Frankford Arsenal, M72-11-1, (May 1972). AD 903 553L

The influence of microstructure upon fracture mode and relative fragmentation performance of steel test cylinders was assessed fractographically by scanning electron microscopy. For the compositions used in this study, a microstructural constituent which provides a path for brittle fracture under dynamic conditions appears to be a necessity for enhanced fragmentation.

I-C-4. Beetle, J.C., J.V. Rinnovators and J.D. Corrie, Proceedings 4th Annual Scanning Electron Microscopy Symposium, Chicago, Illinois, p. 137, (1971)

The present investigation was directed toward studying by scanning electron microscopy (SEM) the fracture morphology of silicon-manganese steel cylinders which were fragmented by explosive loading. The combined effects of high strain rates, transient pressures, and shock waves generated during explosive loading produce unusual behavior in metals. Direct observation of these effects during fracture is difficult because of the extremely short times involved. Indirect techniques, such as optical and metallographic examination, however, have been employed in several studies. Such studies have provided useful information regarding deformation and fracture of materials induced by explosive loading. It was anticipated that the fracture modes would be readily determined using the SEM technique and that the results of the study would lead to a better understanding of the fracture process.

I-C-5. Clark, E.N. and I.P. Juriaco, "Mechanics of Fragmentation of Cylinders," Proceedings of the Army Symposium on Solid Mechanics, (October 3-5, 1972). To be published

The phenomena of fragmentation are described. Two modes of failure occur. For one type, cracks initiate on the outside surface, travel in a shear direction toward the inside and at some point transfer to propagation an adiabatic shear zone to the inside surface. Another mode is fracture propagating in a radial direction and then following an adiabatic shear zone. Radial cracking originates within the material, occurs much earlier than shear cracking, and results from wave-propagation phenomena. The depth of radial cracking is shown to be governed by the temperature of the material. The number of cracks produced in a section of a cylinder correlates with the theory of Mott if room-temperature static mechanical properties are utilized; however, a better relationship can be obtained by allowing for variation of the number of flaws used by Mott's formula. It is not possible to use such an explanation to correct the Mott constants for all materials, however. It is concluded that these results justify a considerably more detailed study of the Mott theory.

I-C-6. Clark, E. N., D. L. Bagnoli and I. P. Juriaco, "Fragmentation Mechanics of Cylinders," Proceedings of the U. S. Army Munitions Command Science Conference, (June 18-19, 1969). AD 506 187L (Paper unclassified)

The first part of this work is a description of observations made on fragments recovered in sawdust. The materials studied in this case were 52100 steel given a heat treatment so as to produce a carbide grain boundary and the same steel with a more conventional heat treatment to give it strength comparable to that of the grain boundary material. All fragmentation cylinders fired were 5 inches long, 2 inches ID, 2.5 inches OD with 2-inch-long aluminum being loaded with composition B. In all fragments studied to date adiabatic shear forms at least part of the fracture surface. Thus it seems desirable that there be many such sites propagating through the material to provide fracture sites. The presence of a large amount of carbon has the further advantage of producing a weak layer of material which fractures quite readily. The whole phenomenon of adiabatic shear, however, needs to be more thoroughly studied. It is probable that the onset of adiabatic shear is controlled by the initiation of cracks on the OD. The question remains as to what controls the density and length of the shear.

I-C-7. Finnegan, S.A. and J. Pearson, "A Metallographic Analysis of Steel Fragments Produced by the Shear-Control Method (U)," Transactions of the 7th NWC Warhead Research and Development Symposium, Naval Weapons Center, TP-5295, Vol. 1, p. 51, (November 16-18, 1971). AD 519 735L (Confidential)

A metallographic study was made of the deformation and gross failure patterns of fragments from explosively loaded, thin-wall cylinders of mild steel, both with and without shear-control grids. The effects of temperature embrittlement were studied by maintaining different cylinders in each of the test groups at ambient temperature, and -110°F prior to detonation. Microhardness measurements and optical microscopy were used to establish failure modes and stress histories of the cylinder walls. Microstructural conditions in the fragments are described in terms of grain deformation, shock twinning, and localized recrystallization in the ferrite phase with associated variations in microhardness. Gross failure involving controlled shearing processes is related to the presence of shear-control grids; and the effects of an outer surface tensile skin in some cylinders are related to low temperature. (U)

I-C-8. Hargreaves, C. R. and R. A. Simpson, "The Role of Adiabatic Shear in the Fragmentation of Steel," Honeywell Independent Research and Development Report. (To be published)

I-C-9. Hoggatt, C.R., and R.F. Recht, "Fracture Behavior of Tubular Bombs," Journal of Applied Physics 39:1856, (1968)

The plastic deformation behavior and modes of fracture exhibited by tubular bomb casings are greatly influenced by the stress state imposed by explosive and inertial forces. These forces combine to produce triaxial compression over a varying inner portion of the tube wall. Noting that compressive hoop stresses would exist over a portion of the wall, Taylor has previously developed a hypothesis for prediction of fracture radius, assuming a radial fracture mode. This paper introduces hypotheses related to the influence of stress state and thermoplasticity upon fracture mode as well as fracture radius. The resulting prediction model closely predicts fracture radius and explains the development of commonly observed shear-lip fractures. It illustrates why radial fractures are typical only when detonation pressures are high.

I-C-10. Lamborn, E.R., "The Fracture of Small Internally Detonated Cylindrical Bodies Partly Prefragmented by Notching. Part I - External Notching," Australian Defense Standards Lab, R-545, (April 1973)

A phenomenological study has been made of the fracture, on detonation of a high explosive filling, of small cylindrical bodies partly prefragmented by external notching. Certain geometric factors are shown to have identifiable effects on the fundamental stress pattern in the cylindrical wall, and the break-up of the cylinder is determined by the deformation and fracture behavior of the material in the net stress pattern.. The interplay of the various contributing geometric and material factors can impose certain restrains on the application of external notching for the control of fragmentation of cylinders of the sizes used, and these restraints are described.

I-C-11. Thornton, P.A., and F.A. Neiser, "Observations on Adiabatic Shear Zones in Explosively Loaded Thick-Wall Cylinders," Metallurgical Trans AIME 2:1496, (1971)

In a current metallurgical investigation being conducted on thick-wall (4-inch wall, 7-inch ID), low-alloy steel cylinders subjected to internal explosive loading, adiabatic shear zones have been consistently observed. To identify the microstructure of the zones and study their role in unstable fracture processes, specimens containing these lines were etched either in 2% Nital or 1% Picral + H_2O and analyzed by microhardness measurements, x-ray diffraction, electron beam microprobe and electron microscopy. Despite the very narrow band thickness encountered in the specimens analyzed (1 to 14 kμ), Knoop hardness reading (50g load) were obtained. These measurements: shear zone 673 to 790 Khn (R_c 50 to 56); and matrix 415 to 480 Khn (R_c) 33 to 38), indicate that the adiabatic shear zone is substantially harder than the matrix and are similar to values for untempered and tempered martensite, respectively, for the 4337-M steel evaluated.

I-C-12. Tucker, D.C., C.R. Hoggatt, W.R. Orr, and R. F. Recht, "Prediction of the Theoretical Behavior and Energy Transfer when Solids are Subjected to Explosive Loading," Denver Research Institute, DRI-2291, (August 20, 1965). AD 475 078

Proposed in this program is a technique to describe the mode of fragmentation and the vector velocity of fragments from center-initiated cylindrical and spherical charges, and the explosive projection of flat plates. The approach taken permits the determination of the system variables from the pressure distribution within the wall and the shape of the case at various times after initiation up to the moment of breakup. The shape of a cylinder at various increments of time can be obtained by solving the equations of motion for an explosively loaded cylindrical wall considering the time of passage of the detonation front with respect to given points on the wall in the axial direction. From the shape of the wall, the radial and longitudinal strains can be obtained. It was found that, in general, there was insufficient longitudinal strain to cause failure normal to the axis and that the fragments must therefore be the result of the coalescence of random longitudinal fractures. A method for obtaining the velocity and direction of the fragments by considering both the shape and acceleration of the wall at the momen of breakup is presented. In addition, a probabilistic method for determining the number of longitudinal fractures is presented, and a procedure for determining the size and number of fragments is proposed. An analysis of the state of stress in an explosively expanding cylindrical wall illustrates the mechanisms of deformation and modes of failure. A summary of the results of a limited experimental program which was designed to check the procedures used in the analysis is also presented. Sample values for several of the variables are given and graphs which indicate the effect of a range of values for parameters that are not fixed are given, along with sample calculations which indicate the utilization of the analytical techniques and formulae.

I-C-13. Walsh, B., "Influence of Geometry on the Natural Fragmentation of Steel Cylinders," Australian Defense Standards Lab, R-533, (January 1973). AD 912 289

The influence of variation in cylinder geometry on the fragmentation and mode of fracture of internally-detonated steel cylinders made from an annealed medium-carbon steel has been investigated. The two principal geometric parameters chosen for study were wall thickness and C/M ratio (the ratio of the weight of high explosive filling to that of the cylinder material). For cylinders of constant C/M ratio but varying wall thickness, a scaling relationship was found to apply, the fragmentation varying in proportion to the original cylinder weight. In cylinders of increasing C/M ratio, where the wall thickness was kept constant, a continuous increase in the fineness of fragmentation was observed and this could be characterized by a simple mathematical expression. The variation in fragmentation possible between geometrically similar cylinders made from two steels to the same commercial compositional specification, but with carbon contents near the extremes of the specified range, was also investigated. It was found that with the geometrics used, large differences in fragmentation could occur due to the effect of carbon on microstructure.

D. EXPLOSIVE FORMING OF SLUGS

I-D-1. Hayes, G.A. and T.L. Herling, "Optical Metallography of Linear-Shaped-Charge Fragments," Naval Weapons Center, TP-4859, (July 1970). AD 878 080

This report presents a metallographic method by which one may reconstruct the linear-shaped-charge collapse process. From the microstructure of recovered elements of collapsed charge liners much can be learned about the deformation processes that have occurred. The microstructures of some typical linear-shaped-charge fragments are illustrated, and some of the more interesting details and their implications are discussed.

I-D-2. Moss, G.L., and S. Toms, R. Vitali, and A. Merendino, "Effect of Target Microstructure on Penetration by Shape Charge Jets," Ballistic Research Laboratories, MR-1739, (April 1966). AD 487 842

Penetration by shaped charge jets into 4140 steel, steel armor and white cast iron has been investigated to determine the magnitude of the effects of target microstructure on penetration. Results prove that target microstructures is a significant variable in the penetration process and that differences due to microstructure can be distinguished after only 50 microseconds of penetration. Differences due to microstructure accumulate during penetration such that total penetrations may differ markedly. A 25% difference was observed in this work. Strain mechanism and crack initiation were different for various microconstituents and are accordingly assumed different for each target. The symmetry of the strain and cavity produced in the 4140 steel depends on the rolling direction.

I-D-3. Whitson, J.C., R.A. Plauson, and C.D. Lind, "Characterization of Linear Shaped Charge (LSC) Ejecta," Trans 6th NWC Warhead Research & Development Symposium, Naval Weapons Center, TP-4835, Vol. 2, p. 597, (October 14-16, 1969). AD 507 165L (Confidential - Paper unclassified)

A study has been conducted of the formation and behavior of the ejecta from a representative single-vane linear shaped charge. Flash radiographs of ejecta have revealed information concerning ejecta dynamic behavior before target impact. A simple hypothesis of ejecta formation based on examination of metallographs of recovered ejecta samples is proposed.

II. METALWORKING

A. BLANKING/PUNCHING

II-A-1. Campbell, J. D.; J. Harding and A. R. Dowling, "Dynamic Punching of Metals," Inst Metals 98:215-24, (July 1970)

Earlier investigations into the response of metals to high-velocity punching are briefly reviewed. A short description is given of an apparatus for measuring loads and displacements during the dynamic punching of metals. Punch load/displacements curves are presented for a selection of metals having a representative range of mechanical properties, at punching speeds between 5×10^{-5} and 900 ips (1.3×10^{-6} and 23 m/sec). From such curves the effect of loading rate on the energy required for punching is determined. Estimates are made of the width of the sheared zone at different punching speeds.

II-A-2. Johnson, W., and F. W. Travis, "High Speed Blanking of Steel," Engineering Plasticity Proceedings, edited by J. Hryman and F. A. Leckie, (1968)

Experiments are described in which 1-1/2-inch-wide strips of 1/8-inch-thick black mild steel sheet were blanked with flat-ended cylindrical punches of 3/8-inch diameter fired from an industrial stud-driver. The effects of (a) radial clearance between the punch and the die and (b) the mass of the punch upon the kinetic energy required to be imparted to the punch for successful blanking are investigated and comparison is drawn with specimens blanked quasi-statically using a universal testing machine. Results are also presented of the penetration of the punch versus kinetic energy of the punch for unblanked specimens and of the mass and polar thickness of the blank versus kinetic energy of the punch for blanked specimens.

II-A-3. Stock, T. A. C., and A. L. Wingrove, "The Energy Required for High-Speed Shearing of Steel," Journal of Mechanical Engineering Sci 13:110, (No. 2, 1971)

Some results are presented relating to the effects of shearing velocity on the energy required for the shearing of both high- and low-carbon steels. Analyses of these results suggest an explanation of some of the apparently contradictory findings of other workers. The results obtained may be explained in terms of the relative imbalance between plastic softening due to adiabatic heating and increase in flow stress due to stain and strain rate.

B. COLD ROLLING

II-B-1. Couling, S. L., J. F. Pashak and L. Sturkey, "Unique Deformation and Aging Characteristics of Certain Magnesium-Base Alloys," ASM Trans 51:94, (1959)

Certain magnesium alloys exhibit unlimited cold-rollability. A plot of percent rolling reduction versus tensile yield strength for these alloys shows the yield strength to reach a maximum at about 15% reduction and to decrease progressively from this point on with

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increasing reductions. Aging the cold-rolled material at a low temperature raises the yield strength; the greater the rolling reduction, the higher the yield strength on subsequent aging. The deformation mechanism operative in these alloys which accounts for their unusual property variations is described and the probable aging mechanism discussed.

C. CUTTING/MACHINING

II-C-1. Black, J. T., "On the Fundamental Mechanism of Large Strain Plastic Deformation," ASME Trans, Paper 70-WA/Prod-11, (1970)

The process of large strain plastic deformation, such as commonly found in the machining process, has been investigated by transmission and scanning electron microscopy techniques. The lamella-shear front nature of deformation in copper and aluminum chips has been elucidated fully, and the occurrence of lamallae has been correlated with crystallographic and metal cutting parameters.

II-C-2. Black, J. T., "Shear Front-Lamella Structure in Large Strain Plastic Deformation Processes," ASME Trans, Paper 71-Prod-1, (1971)

The examination of the surface morphology of copper, aluminum, and steel chips produced by standard shop machining processes through the use of scanning electron microscopy has led to a more fundamental understanding of large strain plastic deformation processes. The interpretation of these findings is discussed in terms of well-documented dislocation mechanisms typically associated with tensile and compression deformation of metal crystals. The effect that such investigations will have on the true understanding of the mechanisms involved in plastic deformation processes is noted.

II-C-3. Lemair, J. C., "Adiabatic Instability in the Orthogonal Cutting of Steel," MS Thesis, MIT, (May 1971)

Discontinuous chips of Fe-18.5Ni.52C tempered martensitic steel were formed by orthogonal cutting at speeds from 0.074 ft/sec to 333 ft/sec for several depths of cut using tools with rake angles of 1, 5, 10, 15, and 20 degrees. Martensite is observed to revert to austenite in a thin band along the sheared edges of the chips for speeds greater than 7.50 in/min and rake angles less than 15 degrees. The existence of austenite is taken as an indication that the temperature of these bands is in excess of 426°C. It is found that only those cutting conditions which create shear-zone temperatures between 100 and 200°C facilitate the formation of austenite. Tensile tests conducted in the range of temperatures from 25 to 314°C reveal austenite on the fracture surface only at temperatures below 200°C. It is suggested that an adiabatic instability and subsequent release of elastic energy from the machine account for the presence of austenite bands.

II-C-4. Lemaire, J.C., and W.A. Backofen, "Adiabatic Instability in the Orthogonal Cutting of Steel," Metallurgical Trans 3:477-481, (1972)

The reversion of Fe-18.5Ni-.52C tempered martensitic steel to austenite under shear was used to study the formation of discontinuous chips by orthogonal cutting. For certain combinations of cutting speed, depth of cut, and tool rake angle, chips with bands of reverted austenite along their sheared edges were formed. Tensile tests on the same material exhibited transformed austenite on the specimen fracture surfaces for tests conducted below 200°C. Metal cutting theory predicts that continuous plastic deformation during chip formation cannot heat the material to its reversion temperature. Analysis of the machine-sample interaction before chip separation shows that adiabatic instability can occur, resulting in localized shearing and a temperature rise to at least A_s. Only those chips which are heated during continuous deformation to temperatures between 100 and 200°C undergo adiabatic instability and reversion.

II-C-5. Pomey, J. "Fundamental Mechanisms in Metal Cutting," Rev. Francaise de Mecanique, p. 73-100, (No. 18-19, 1966)

From a review of available information on plasticity, on chip formation, and on friction due to sliding between chip and tool, it is concluded that lack in present knowledge of these phenomena makes additional studies mandatory. Three directions of scientific investigations in these areas are indicated, and suggestions are made regarding various techniques by means of which phenomena of chip formation and slipping between chip and tool can be dissociated in cutting tests.

II-C-6. Pomey, J., "Fundamental Mechanisms of Metal Cutting," Proc. Seminar on Metal Cutting (O.C.D.E.), Paris, p. 29-78, (1966)

Metal cutting is considered on the basis of the distinct, but interrelated, mechanisms of (a) plasticity in relation to chip formation and (b) friction between chip and tool. Slip, stress, shear, force, time, temperature, diffusion, wear and tool-life effects involved are mathematically and otherwise considered. Cutting, friction, and wear testing, and attack-angle, cutting-rate, and metallurgical factors are reviewed. Research approaches are suggested.

II-C-7. Pomey, J. "Remarks on Plastic Chip Formation (During Machining)," Proc. Seminar on Metal Cutting (O.C.D.E.), Paris, p. 99-110, (1966)

Theoretical and practical aspects of plastic chip formation are considered in the light of a principal mechanism involving slip in an average direction, as a function of the direction of travel of the tool cutting edge in relation to the work-piece. Specific reference is made, on the basis of metallographic observations by Svahn, to pseudo-periodic development, within the chip of strained regions related with surface waves upon it. Special torsion tests and high-speed-cinematography studies in this respect are mentioned. In discussion G.C. Cao critically considers the parallel-slip and other concepts in the light of his and other chip-formation models.

II-C-8. Pomey, J. "Remarks on Plastic Flow of Chips in Metal Cutting." Rev. Francaise de Mecanique, p. 101-4, (No. 18-19, 1966)

A photograph and drawing reproduced from O. Svahn's microphotograph show pseudoperiodic development of more or less strained zones in the chip, which are closely connected with surface waves. This phenomenon is clearly explained by distribution instability which may occur in adiabatic plasticity. Results indicates need for special torsion tests of metal and of cutting tests with high-speed photography.

II-C-9. Recht, R. F., "Catastrophic Thermoplastic Shear," Journal of Applied Mechanics 31:189, (No. 2, 1964)

Dynamic plastic behavior of materials is influenced by internally generated temperature gradients. These gradients are a function of thermophysical properties as well as strain rate and shear strength. Criteria are presented for the prediction of catastrophic shear in materials. Catastrophic shear occurs when the local rate of change of temperature has a negative effect on strength which is equal to or greater than the positive effect of strain-hardening. Catastrophic slip is an influential deformation mechanism during high-speed machining and ballistic impact. Structural failure may occur during dynamic loading of components, which are designed without regard to the specific sensitivity of certain materials to catastrophic shear.

II-C-10. Svahn, O., "Plasticity in Cutting," Proc. Seminar on Metal Cutting, O. C. D. E., p. 79-94, (1966)

The importance of plastic deformation in relation to friction, temperature, cutting forces, machinability, tool life, surface finish, and other factors in metal cutting is emphasized. A cooperative research program comprising formulation of true stress/strain diagrams, recording of cutting force, and metallographic observations is outlined, and results obtained are illustrated. Chip formation, strain-hardening effects, necking-type instability, chemical interactions, adhesion, and definition of machinability are among the aspects raised in discussion.

II-C-11. Von Turkovich, B. F., "Mechanics of Cutting," Proc 1st Intl Cemented Carbide Conf, SME Tech Paper MR71-903, (1971)

Plastic deformation and fracture, normally confined to a volume of metal ahead of the tool, are strongly affected by the conversion of mechanical work into heat. The modern theory is based upon the micromechanics of crystalline defects interactions and the thermodynamic state of material. The cutting process appears as a stationary sequence of adiabatic slips, with the frequency governed by the thermal conductivity and the initial temperature of the work material. The details of the process are presented in the light of dislocation theory, and the results are correlated with continuum mechanics for technological purposes. The main conclusion is the generalization of computations leading to rapid and reliable estimates of cutting forces, temperature, and surface finish.

II-C-12. Von Turkovich, B. F., and M. E. Merchant, "On a Class of Thermo-Mechanical Processes during Rapid Plastic Deformation (with Special Reference to Metal Cutting)," Annals of C. I. R. P. 21:15-18, (No. 1, 1972)

The phenomenon of conversion of mechanical work into heating during plastic deformation and the resulting effect of heat production on the mechanical properties of the deforming material is considered. In particular, a peculiar process called "adiabatic shear deformation" is illustrated; this process is frequently thought to be responsible for the narrow deformation zones in many rapid metal working operations. A simplified analysis of the deformation process taking place in these narrow shear zones is presented.

II-C-13. Wright, P. K., "Metallurgical Effects at High Strain Rates in the Secondary Shear Zone of the Machining Operation," Metallurgical Effects at High Strain Rates, edited by R. W. Rohde, pub. by Plenum Press, p. 547-558, (1973)

The paper analyses the strain rates and conditions of deformation that occur during semi-orthogonal metal machining. Emphasis is placed upon the area termed the secondary shear zone or flow zone. It is demonstrated that, when machining at high rates of metal removal, conditions of "seizure" occur at the chip-tool interface to cause a high strain rate deformation within the chip flow zone. These processes promote considerable adiabatic heat generation with consequent metallurgical changes in the chip structure and a reduction in the stress acting along the interface.

D. EXTRUSION

II-D-1. Buffet, J., and B. Jaoul, "Actual Deformation During Extrusion," Rev. de Metallurgie (Memoirs) 57:827-833, (September 1960). In French

II-D-2. Dower, R. J., "The High-Speed Extrusion of Some Common Metals," National Engineering Laboratory, R-188, (June 1965)

Aluminum, copper, alpha-brass and En2E mild steel have all been successfully extruded using impact speeds of up to 36-1/2 ft/sec. Studies of the mechanical properties and microstructures of rods extruded at high speed show that the temperature rise due to the adiabatic nature of the process has a considerable effect, complete recrystallization occurring in aluminum and copper at extrusion ratios greater than 8:1 and in alpha-brass at extrusion ratios greater than 23:1, at impact speeds of 36-1/2 ft/sec. No greater "formability" was observed, and attempts to extrude HD_{44} aluminum-magnesium-silicon alloy and DTD363A aluminum-zinc-magnesium alloy at high extrusion ratios resulted in complete disintegration of the product.

II-D-3. Herenguel, J. and P. Lelong, "A Metallurgical Mechanism Particular to Extrusion; Hyperwelding," Rev. de Metallurgie 55:1057-1064, (July 1958). In French

II-D-4. Hirst, S. and D. H. Ursell, "Some Limiting Factors in Extrusion," Metal Treatment and Drop Forging 25:409-414, (October 1958)

Certain alloys with high strength at their working temperatures pose difficult problems in extrusion. In unlubricated extrusion, the conditions involved often cause severe restrictions on extrusion ratio and speed, and, to widen the field over which the process is possible, lubrication techniques have been evolved. Limitations on extrusion ratio imposed by the dimensions and preheat temperature of the billet for any given press capacity may be expressed in the form of a family of curves on a graph of extrusion ratio against preheat temperature. Extrusion ratio is also restricted by unacceptable temperature rise due to heat input, and this limitation may be expressed in another family of curves on the same graph, thus defining an enclosed area in which extrusion is possible for any given conditions. This basic graph is extended to cover different press capacities, ram speeds, and coefficients of friction; it is shown that it may also be used to predict a phase transformation temperature being reached during extrusion. The relative potentialities of lubricated and unlubricated extrusion are compared.

II-D-5. Kiszka, J.C., and E.H. Kottcamp Jr., "High Strain Rate Forming by Pneumatic-Mechanical Equipment - Phase I: Extrusion of 1100-0 Aluminum," Frankford Arsenal, R-1745, (December 1964)

II-D-6. Lawson, G.A., "Mechanical Properties of Cold-Extruded Aluminum Rods," National Engineering Laboratory, R-51, (September 1962)

II-D-7. Osina, V., "Forming of Metals at High Rates and Energies," Metal Treatment, 33:193-204, (May 1966)

This article is concerned with changes in the microstructure of steel during bulk deformation and at high velocities of the tool. During experimental research in Czechoslovakia on forward extrusion at rates of the order of 100 m/sec, it has been found that an unfavorable effect on the strength of the components is produced. In the structure, bands appear which the author classifies as a martensitic structure. He attributes their formation to the action of heterogeneous slips. A theory explaining the mechanism of the stated structural changes is elucidated.

II-D-8. Pomey, J., "On a Phenomenon of Adiabatic Plasticity," Annals of the C.I.R.P., 13:93-109, (March 1966)

If we consider a homogeneous spatial distribution of all the physical and mechanical parameters in a solid body in the course of a plastic and adiabatic deformation by simple one-direction slipping, this distribution becomes unstable and a layer appears in which easy slips occur at high temperature through creep. This layer separates the solid body into two fields which may be submitted to two different systems of stresses, for example, elastic on one side and plastic on the other. The physical characteristics of the material which is the most important to consider is $\partial\tau/\partial\theta$ which varies in a similar manner to $\partial\Delta/\partial\theta$. This phenomenon can be studied by experiments on shearing by extrusion in simple test pieces. In seizure by dry slip friction between two solids, this phenomenon explains the transfer of metal. In metal cutting it explains the process of the formation if a built-up edge; the reason for the existence of an economical rate for cutting and the speed limit at which the tool becomes blunted. It also takes place in extrusion, in hot stamping, in cold heading, in punching, etc.

II-D-9. Pomey, J., A. Royez, P. Mathon, and M. Mouflard, "Etude sur le filage a froid des aciers," C. I. R. P. Annalen, 9:185-193, (1963)

This paper deals with the cold extrusion of steels, specifically extrusion of soft steel and iron billets. The use of lubricants and pretreatment of billets to facilitate ease of extrusion are investigated. Results indicate that soft iron billets can be extruded more easily if nitrided, but steel billets may not be so processed for fear of cracking during extrusion. Extrusion pressure, lubricants and strain endurance are considered.

II-D-10. Pugh, H. L. D., M. T. Watkins, and G. S. Lawson, "Cold Extrusion of Aluminum and Aluminum Alloys," Metal Treatment and Drop Forging 31:82, (March 1964)

II-D-11. Singer, A. R. E., and J. W. Coakham, "Factors Affecting Temperature During the Extrusion of Non-Ferrous Metals," Metallurgia 60:239, (1959)

During the process of extruding a metal through a die, the heat content of the billet may be increased by such factors as friction at the metal container interface, severe plastic deformation in the die zone, and die friction. A certain amount of this heat generation is offset by loss of heat from the billet by conduction. In this paper, the authors consider the heat balance during extrusion under a range of conditions, and examine the progress made in controlling the temperature variations arising.

II-D-12. Svahn, E., and P. Boije, "Investigation Concerning the Semi-Cold Working of Material," Annals of the C. I. R. P., 13:417-424, (1966)

II-D-13. Wallace, J. F., "Adiabatic Deformation in Impact Extrusion," Journal of the Institute of Metals 90:38-41, (1961-1962)

Except for a small fraction retained by micro- and macro-residual strains, the work done in the plastic deformation of metals is converted into heat. At very high strain rates adiabatic conditions will be attained in individual elements of material as they are deformed, and the effect of the heat of deformation on the flow and forces required should be immediate and continuous rather than cumulative. Most materials exhibit a reduction in flow stress with increase of temperature; so, with adiabatic deformation, the work done to produce the deformation, and hence the deforming forces, should be less than in isothermal deformation. High strain rates have been obtained by extruding lead and aluminum under the impact of a drop hammer, and experimental measurement of the heat content of the extrusion suggests that the entire process is substantially adiabatic. Evidence that the basic deformation pressure under these conditions is less than at low speeds is given by experiments after the total extrusion pressures are corrected for the inertia forces. It is suggested that this reduction of extrusion pressure may be obtained with extrusion velocities at which the inertia component of the load would be negligible and that difficult extrusion may be more easily performed with repeated small impacts.

E. FORMING

II-E-1. Backofen, Walter A., Deformation Processing, pub. by Addison-Wesley, 326p., (1972)

II-E-2. Boulger, F.W., "High-Velocity Forming," Defense Metals Information Center, R-226, p. 13, (1966). AD 488 644

II-E-3. Elfmark, Jiri, "Effect of Deformation Rate on Hot Formability of Steels," Hutnicke Listy 27:626-630, (September 1972). In Czech

A review, concerning the effect of the deformation rate on the hot formability of steels is presented, and additional information, in the form of experimental results, is given. On the basis of known results, an equation expression the thermodynamics of the deformation of a torsion test specimen was computed. The equation was valid for a number of variously alloyed steels subjected to deformation at rates of between 10^{-3} and 10/sec.

II-E-4. Farlik, A. and V. L. Osina, "High Energy Rate in the Forming of Metals," Buletinul Institutului Politechnic 8:341, (1962)

II-E-5. Gerds, A. F., "Adiabatic Conditions in Deformation Processing," Defense Metals Information Center, R-243, Vol. 3, p. 117, (1967)

II-E-6. Rinehart, J. S., and J. Pearson, Explosive Working of Metals, pub. by Pergamon Press, 351p., (1963)

II-E-7. Truelock, D.W., J. R. Russell, and C. M. Phelon, "High-Velocity Forging," Air Force Materials Lab, TR-68-374, (December 1968) AD 858 513

This is a manufacturing methods program to investigate the dynamic response of selected aerospace alloys deformed by upset forging from room temperature to 1950°F at impact strain rates from quasi-static (100 in/in/sec.) to 8000 in/in/sec.

II-E-8. Wistreich, J. B., "Fundamentals of Wire Drawing," Metallurgical Reviews 3:97, (No. 10, 1958)

III. METALLURGICAL STUDIES

A. DEFORMATION HARDENING/SOFTENING

III-A-1. Andrew, J. H.; H. Lee, and L. Bourne, "Effect of High-Speed Deformation on Steel," Iron & Steel Institute Journal 165:37, (1950)

> The effect of rapid deformation on steel by means of a dynamic load impact has been investigated and the results confirm those of previous workers, via., that the deformation is extremely localized giving rise to the formation of a white band. X-ray examination shows this band to contain austenite and martensite.

III-A-2. Conrad, H., "Thermally Activated Deformation of Metals," Journal of Metals 16:582-588, (1964)

> The dynamic nature of the plastic deformation of metals and its relation to specific thermally activated dislocation mechanisms are discussed. Experimental techniques for evaluating the deformation parameters needed to identify the rate-controlling dislocation mechanism are described. The mechanisms that appear to be controlling in various temperature ranges are listed. Such fundamental lattice properties as the force-distant curve for a thermally activated process, the energy of a dislocation kink or of a jog, the stacking fault energy, and the activation energy for self diffusion are indicated to be derivable from macroscopic mechanical property data.

III-A-3. Culver, R. S., "Adiabatic Heating Effects in Dynamic Deformation," Proceedings 3rd International Conference of the Center for High Energy Forming, p. 4.3.1, (1971)

> A thermal instability strain, based solely on thermal and mechanical properties, is hypothesized for the case of uniform, adiabatic, plastic. A mathematical model has been presented to predict the degree of adiabaticity existing in the deforming region. Torsional impact experiments were carried out on mild steel, 6061-T5 aluminum, and commercially pure titanium to investigate the existence of the thermal instability strain. The titanium, which has a low theoretical thermal instability strain, underwent strain localization at approximately the predicted value, while the other two materials failed at strains well below their respective instability strains but somewhat above the static fracture strains.

III-A-4. Culver, R. S., "Thermal Instability Strain in Dynamic Plastic Deformation," Metallurgical Effects at High Strain Rates, edited by R. W. Rohde, pub. by Plenum Press, p. 519-530, (1973)

> From the results presented, it can be tentatively concluded that the theoretical prediction of the instability strain is valid for materials with a low instability strain, i. e., in those cases where the instability strain is approximately equal to the conventional fracture strain. For those materials for which the thermal instability strain is well above the static fracture strain, the maximum in the torque curve does not cause catastrophic failure but rather the initiation of a diffuse neck. Further tests on other materials with high and low values for shear strain will be made to clarify these points.

III-A-5. Dieter, G. E., "Hardening Effect Produced with Shock Waves," Strengthening Mechanisms in Solids, pub. by American Society for Metals, p. 279-340, (1960)

III-A-6. Fell, E. W., "Strain in Steel," Carnegie Scholarship Memoirs 16:101-129, (1927)

Experimental work was undertaken to investigate the detection and the nature of permanent strain in steels which would be of value to practical metallurgists and engineers. Since permanent strain occurs before almost all failures in service, a knowledge of the mechanism of strain may well lead to the prevention of some failures.

III-A-7. Glass, C. M.; G. L. Moss and S. K. Golaski, Response of Metals to High Velocity Deformation, pub. by Interscience, p. 115, (1961)

Experiments were conducted on the high-velocity deformation of single-crystal and polycrystalline metals, using explosive systems to produce the loading on the metals. The results from these experiments indicate the metal properties influence the deformation, even at pressures of 300 Kbar. In single-crystal studies, framing camera records show that internally loaded aluminum cylinders begin to deform nonuniformly during the first reflection of the compressive wave from the free surface, and the pressures calculated in these experiments are approximately 20 Kbar at the free surface, and 250 Kbar at the metal-explosive interface. Copper single-crystal studies show that the deformation takes place along conventional systems and that the deformation structures observed may be accounted for after the passage of the first compressive wave. In addition, twin-like structures formed are analyzed, using x-ray techniques, as being kink bands, within which no reasonable deformation is observed. Several interesting structural changes in steel produced by intense pressures are discussed. Microscopic studies of fracture surfaces indicate that the fractures begin at inclusions, and the propagation of the fracture surface is a function of the number and types of inclusions. Indications are that fracture should be considered a function of impulse, rather than pressure by itself.

III-A-8. Price, R. J., and A. Kelly, "Deformation of Age-Hardened Alloy Crystals. II — Fracture," Acta Metallurgica 12:979, (1964)

Single crystals of Al Cu, Al Ag, and Al Zn, aged to contain GP zones, fracture by shear on a {111} plane in a <110> direction followed by crack propagation. There are three stages in the fracture. First, coarse slip bands appear at a constant resolved shear stress which depends on temperature for a given material. Secondly, a large shear occurs on one of these and lastly a crack forms at the foot of the shear step produced. The first two stages also appear in compression. The coarse slip bands which initiate fracture appear to be produced at such a shear stress that the stress for their appearance minus the critical resolved shear stress is roughly constant in a given temperature although slightly affected by alloy content. It is concluded that the appearance of the coarse slip bands is a property primarily of the work-hardened matrix and not of the precipitates, and that they appear when some barrier formed during work hardening is broken down.

III-A-9. Rinehart, J. S., and J. Pearson, Behavior of Metals Under Impulsive Loads, pub by American Society for Metals, 256p., (1954)

III-A-10. Shankhla, V. S., and R. F. Scratton, "Free Plastic Compression of Pure Metals," Journal of Applied Mechanics 36:1121, (No. 4, 1970)

The dynamic compression of a billet by the impact of a falling weight is analyzed with reference to the general plastic properties of pure metals. Theoretical results are compared with the results of published experimental data for pure lead. It is shown that, for lead, the form of the stress-strain curve is little influenced by changes in strain rate during deformation. The strain-hardening coefficient is however found to be strongly influenced by the temperature changes associated with the adiabatic deformation. The position of the maximum in the stress-strain curve is sensitive to the value of the initial strain rate. A method is suggested whereby isothermal stress-strain relationships may be extended to include the effects of adiabatic thermal softening.

III-A-11. Sulijoadikusumo, A. U., and O. W. Dillon Jr., "Work Softening of Ti-6Al-4V due to Adiabatic Heating," Metallurgical Effects at High Strain Rates, edited by R. W. Rohde, pub. by Plenum Press, p. 501-518, (1973)

Many investigators have shown that, at high strain rates at elevated temperature (1300-1900°F) and for large deformations, Ti-alloys exhibit considerable work softening. The mechanism of such metal softening is different from the one encountered in processes at lower strain rates (creep). In the high-temperature range, Ti-6Al-4V is known to be both temperature- and strain-rate sensitive; i. e., an increase in strain-rate will increase the flow stress, and an increase in temperature significantly decreases the flow stress. Therefore, thermal changes strongly influence the metal behavior during the deformation. When metal is undergoing large plastic deformation, approximately 95% of the plastic work is converted into heat almost instantaneously (less than 1 msec). This rapid dissipation of large amounts of energy causes temperature rises in the material. Such a heating would cause the metal softening during the process relative to what would be observed in isothermal deformations.

B. CRYOGENIC DEFORMATION

III-B-1. Basinski, Z. S., "The Instability of Plastic Flow of Metals at Very Low Temperatures," Royal Society Proceedings 240A:229, (1957)

The low-temperature unstable plastic deformation of aluminum alloys is described. It is shown that discontinuities in the stress-strain curve are caused by a localized temperature rise produced during the deformation. The calculated magnitudes of the drops in load and the transition temperature between smooth and discontinuities flow agree reasonably well with the experimental observations. It is believed that all metals should exhibit unstable deformation at sufficiently low temperatures.

III-B-2. Basinski, Z. S., "The Instability of Plastic Flow of Metals at Very Low Temperatures," Australian Journal of Physics 13:354, (1960)

Evidence is presented to show that the load drops observed in most metals at very low temperatures arise from thermal instability rather than mechanical instability of the lattice. Measurements of the temperature rise are described.

III-B-3. Chin, G. Y.; W. F. Hosford Jr. and W. A. Backofen, "Ductile Fracture of Aluminum," AIME Trans 230:437, (1964)

The ductile fracturing process was studied in single-crystal and polycrystalline aluminum deformed in tension over a temperature range from 295 to 4.2 K. At temperatures as low as 77 K, the fracture of "inclusion-free" material, including zone-refined aluminum, was by rupture (~100% RA). At 4.2 K, fracture was brought on by adiabatic shear. Metallographic examination did not disclose any voids or slip-band microcracks, thus negating for inherently ductile metals any mechanism of void nucleation by vacancy condensation or of cracking due to dislocation pile-ups. In high-purity aluminum not treated to be inclusion-free, fracture at temperatures as low as 45 K was of the double-cup type and a result of void formation. The reduction-of-area decreased as temperature was lowered, corresponding to the earlier appearance of voids. Such behavior was rationalized in terms of a larger increase, with decreasing temperature, in the flow stress relative to the strength of the inclusion-matrix interface. Evidence for low-temperature adiabatic shear was fround in discontinuous flow at 4.2 K, in the transition to a localized shear fracture at low temperatures, and in the suppression of shear fracture with an elastically hard pulling device. A simple analysis for the initiation of adiabatic shear permitted a general correlation of the various contributing factors. It has been pointed out that the duration of shear depends upon effective mass and elastic stiffness of the deformation system.

III-B-4. Hosford, W. F.; R. L. Fleischer and W. A. Backofen, "Tensile Deformation of Aluminum Single Crystals at Low Temperature," Acta Metallurgica 8:187, (1960)

Tension tests on aluminum single crystals of approximately (001), (111), (112) and (123) axial orientations were made at 4.2, 77, 200, and 273 K. It was a general observation that the hardening rate passed through a maximum and then decreased continuously with increasing stress, the decrease being less rapid at the lower temperatures. There were no findings, under any circumstance, of a constant stage II slope in the stress-strain curves. At 273°K, after initially rapid hardening, (001) crystals deformed primarily by operation of two slip systems with conjugate relationship; multiple necks were formed but the accompanying lattice rotation prevented failure by necking until large strains. At lower temperatures, all four stressed slip directions were active in the (001) crystals, and hardening continued to higher stresses. With the four directions, two perpendicular sets of Lomer-Cottrell barriers could form, as contrasted to one set at 273 K, thus producing greater hardening. Slip markings at the lower temperatures tended to follow (110) traces, but this may be explained by a fine mixture of cross slip on two (111) planes, necessary to avoid the barriers. In (111) crystals, approximately equal operation of the three favored directions at all temperatures prevented lattice rotation and maintained a high hardening rate.

C. DUCTILITY

III-C-1. Banks, E. E., "The Ductility of Metals under Explosive Loading Conditions," Institute of Metals Journal 96:375, (1968)

The ductility behavior of two steels and two aluminum-base alloys has been investigated at high strain rates (4.5×10^3 to 3.5×10^4/sec). Specimens were in the form of cylinders, and the high-rate loading was obtained by the detonation of internal explosive charges. Under these conditions, the strain at fracture is a function of expansion velocity, and this strain may be either greater or less than the tensile value. This behavior is examined in terms of the rate-dependence of the stress/strain characteristics of the materials, shock-induced temperature rises, and the increased compressive stresses resulting from the non-equilibrium method of loading.

III-C-2. Dieter, G. E., "Introduction to Ductility," ASM Seminar on Ductility, October 14-15, 1967, p. 1-30, pub. by American Society for Metals, (1968)

The subject of ductility is approached by defining ductility and by discussing the methods of measuring this property and the difficulties of arriving at a true assessment. The engineering stress-strain curve and the true stress-true strain curve are analyzed, and the procedures for plotting them are explained. Fracture mechanics and the measurement of fracture toughness as an approach to problems of ductility are examined. The effects of grain size and other features of the microstructure of metals and of temperature and strain-rate are reviewed. Ductility data are given for Al-3.2%Mg, 2024, 7075 and 2219 Al alloys and for several steels, Cu alloys, Ni and Ni alloys.

III-C-3. Gensamer, M. "Strength and Ductility," ASM Trans 36:30, (1946)

III-C-4. Rogers, H. C., "Effects of Material Variables on Ductility," ASM Seminar on Ductility, Oct 14-15, 1967, p. 31-61, pub. by American Society for Metals, (1968)

Three sets of factors controlling ductility in commercial metals and alloys are examined. One set comprises certain properties of the pure metal. Another is made up of structural effects and includes the possibility of void nucleation by dislocation interaction alone, the effects of holes and particles and the embrittling effects of a special distribution of the softer phase in a two-phase system. The third set pertains to the gross external geometry (size, shape, stress state and surface condition) of the metal being deformed. Differences in ductility and in the appearance of fracture under different conditions are attributed to the factors that control the generation of new slip surfaces. The most important factors are those that influence the tendency of the pure metal to concentrate strain (such as dislocation behavior, stacking-fault energy, temperature, adiabatic heating and the rate of strain hardening) and those that promote the nucleation of new slip surfaces at many internal sites. The density of 6063-T6 Al alloy, drawn under differently externally applied hydrostatic pressures as a function of thickness, is shown in a set of curves.

D. PLASTICITY

III-D-1. Alekseev, N. and G. P. Kulikov, "Plasticity Under Conditions of Local Heating," Samoletstroenie i Teknika Vozdushnogo Flota 26:80-86, (1971). In Russian

A method is developed for the determination of plasticity under conditions of local heating encountered in processing high-melting-point metals with pressing mills. The dependence of plasticity on the temperature gradient is used to define the parameters of technological processing when local heating is used. The temperature gradient is determined by computing thermal processes during welding. Computations are shown for both movable and fixed plates of given thickness when using a fixed, constant-power source that gives a normal-curve heat distribution upon the plate.

III-D-2. Hill, R., Mathematical Theory of Plasticity, pub. by Oxford Univ. Press, 354p., (1950)

III-D-3. Nadai, A., Plasticity; Mechanics of the Plastic State of Matter, pub. by McGraw-Hill, 349p., (1948)

III-D-4. Pomey, J., "On Phenomenon of Adiabatic Plasticity," C. R. Acad. Sci. 258:4204-5, (April 27, 1964)

When a homogeneous medium is subjected to unidirectional parallel plane sliding under adiabatic conditions, uniform separation of flow can easily be disturbed and a high-temperature strong sliding layer is formed which separates the body into two domains. The deformation behavior of domains can be different; this phenomenon governs most metal forming processes and, particularly, shock forming of refractory metals.

III-D-5. Pomey, J., "Outline of Adiabatic Plasticity," Rev. Francaise de Mecanique, p. 5-20, (No. 12, 1964)

Spatial distribution of physical and mechanical parameters in a solid body during plastic adiabatic deformation by simple one-directional slips is investigated. At high temperatures, the appearance of a slip layer due to plastic flow is observed; this boundary layer separated the body into two domains which may be subjected to two different types of stresses, e.g., elastic on one side and plastic on the other. The effect of this phenomenon on the behavior of metals during various forming and machining processes is studied theoretically and experimentally.

III-D-6. Taylor, G. I., and H. Quinney, "Latent Energy Remaining in a Metal after Cold Working," Royal Society London Proc 143:307-326, (1934)

Measurements of the latent energy remaining in metal rods after severe twisting are described. Very much more cold work can be done on a metal in torsion than in direct tension. It is found that, as the total amount of cold work which has been done on a specimen increases, the proportion which is absorbed decreases. Though saturation was not fully reached even with twisted rods, curves representing the experimental results for copper indicate that it would have been reached at a plastic strain very little greater than the strain at fracture. The amount of cold work necessary to saturate copper with latent energy at 15°C is thus found to be slightly greater than 14 calories per gram. By using compression instead of torsion, it was found possible to do much more cold work on copper than this, and compression tests revealed the fact that the compressive stress increases with increasing strain till the total applied cold work was equivalent to 15 calories per gram. No further rise in compressive stress occurred with further compression even though the specimen was compressed till its height was only 1/53rd of its original. The fact that the absorption of latent energy and the increase in strength with increasing strain both cease when the same amount of cold work has been applied suggests that the strength of pure metals may depend only on the amount of cold work which is latent in them.

E. FRACTURE

III-E-1. Backofen, W. A., "Metallurgical Aspects of Ductile Fracture," Fracture of Engineering Materials, pub. by American Society for Metals, p. 107-126, (1959)

II-E-2. Gruntfest, I. J., "A Note on Thermal Feedback and the Fracture of Solids," AIME Metallurgical Society Conference, Fracture of Solids, Vol. 20, p. 189, (1962)

Thermal effects accompanying the deformation and fracture of solids have often been noted, and they are sometimes conspicuous. A preliminary account of some current analytical and experimental studies of heating accompanying fracture is given. The analysis leads to an unambiguous upper limit for the mechanical strength of solids. In addition, time effects and size effects are introduced in a novel and natural fashion. Furthermore, the ideas of the relevance of thermal conductivity and the temperature coefficients of mechanical response to fracture phenomena generated in this analysis could be useful in the rational development of new and stronger materials. The experiments suggest that even in some of the usual "static" fracture experiments, thermal effects need not be negligible. This new material in no way contradicts other atomistic and phenomenological theories of the fracture process presented at this symposium. It is indeed altogether complementary to them.

III-E-3. Irwin, G., "Fracture Dynamics," Fracturing of Metals, pub. by American Society for Metals, (1948); also in ASM Trans 40B:147-166, (1948)

Attempts to clarify recent developments in the dynamics of rapid fracturing of ductile metals are presented by means of a discussion of the results of some Navy research on ductile and brittle fracture of ship-plate steels. A brief mathematical derivation of the velocity of brittle fracture is given.

III-E-4. McClintock, F. A., "On the Mechanics of Fracture from Inclusions," ASM Seminar on Ductility, Oct 14-15, 1967, p. 255-277, pub. by American Society for Metals, (1968)

A mathematical treatment is presented of the process of fracture due to inclusions considers stress and strain around inclusions, the growth and coalescence of holes initiated by inclusions, the termination of ductile fracture by localized shear and statistical fluctuations in the inclusion spacing. It is found that fracture occurs at half or less of the strain predicted by the uniform growth and coalescence of holes. Preliminary analysis indicates that this difference may be due in part to instabilities causing strain concentrations and statistical effects causing agglomerations at the potential nucleus of the crack.

III-E-5. Nadai, A., Theory of Flow and Fracture of Solids, Vol. 1, pub. by McGraw-Hill, 572p., (1950)

III-E-6. Tegart, W. J., "Adiabatic Shear Fracture," Elements of Mechanical Metallurgy, pub. by Macmillan Co., p. 217-219, (1967)

III-E-7. Zener, C., "Micro-Mechanism of Fracture," Fracturing of Metals, pub. by American Society for Metals, p. 3-31, (1948)

III-E-8. Zener, C., and J. H. Hollom, "Plastic Flow and Rupture in Metals," ASM Trans 33:163, (1944)

In this paper many phenomena not previously understood are shown to be explicable in a qualitative manner by a single type of imperfection which may be quite precisely defined, namely by the concept of microscopic cracks. These phenomena include the decrease in the rate of strain hardening in torsion at large strains compared with the strain hardening in tension, the elongation which accompanies large angles of twist, and the effect of a prior twist upon the type of tensile fracture. A quantitative analysis, first suggested by Griffiths, is applied to these cracks. This analysis attempts a correlation of the fracture stress with the size of these micro cracks which are correlated with certain elements of the microstructure.

F. STRUCTURE AND PHASE TRANSFORMATION

III-F-1. Andrew, J. H.; H. Lee and D. V. Wilson, "An X-ray Investigation of Structural Changes in Steel Due to Cold-Working," Iron & Steel Institute Journal 165:374, (1950)

X-ray examinations on high-carbon and alloy steels after cold-working by compression have failed to reveal the presence of austenite in unfractured test-pieces. It is shown, however, that austenite may be formed on the surface of shear fractures. An x-ray investigation of the influence of severe cold-working on cementite in steel has been made, and evidence of large residual strains in such cementite, together with some tendency towards preferred orientation, has been found.

III-F-2. Borgese, S. F. and W. J. Pantaione, "A Special Report on the Tempering Behavior of Deformation Bands in 52100 Steel," SKF Industries Inc., (May 1967). AD 816 394

The deformation bands which form in cyclically stressed rolling bearings were tempered in the electron microscope to establish the carbon level in solid solution in these areas. In most of the specimens no carbide precipitation occurred in these regions when they were tempered at 550°C. In one specimen, tempered at 325°C, many tiny carbide formed at the cell walls inside the deformation bands. These observations are consistent with a theory proposed for the growth of lenticular carbides which form at the boundaries of the deformation bands in 52100 steel during cyclic stressing. The deformation bands which are free of excess carbon are regions where lenticular carbides have grown and depleted the areas of carbon while the bands which were supersaturated with carbon were free of lenticular carbides. It is concluded that the lenticular carbides grow by utilizing the excess carbon in the deformation bands and continue to grow until the level inside the deformation band has reached the equilibrium concentration.

III-F-3. Bush, J. J.; W. L. Grube and G. H. Robinson, "Microstructural and Residual Stress Changes in Hardened Steel Due to Rolling Contact," ASM Trans 54:390-412, (1961)

The changes in microstructure, hardness, and residual stresses occurring in SAE 52100 steel as a result of rolling contact operation are described. The relationship of running time and contact load to the extent and appearance of the microstructural alteration is examined, and evidence is presented to show that a threshold stress exists, below which no gross structural alteration occurs. The nature of the alteration, as revealed by electron metallography, suggests a possible mechanism for the observed structural changes. The effect of rolling contact on development of macroscopic residual stresses in ball bearing races and in simple roller specimens is discussed. Also included are data showing the alteration, by rolling contact, of residual stress patterns introduced by prior surface mechanical working. The possible correlation of these stress changes with the microstructural alterations is investigated.

III-F-4. Glenn, R. C. and W. C. Leslie, "The Nature of 'White Streaks' in Imported Steel Armor Plate," Metallurgical Transactions 2:2945, (1971)

Electron transmission and diffraction studies suggest that the "white streaks" are due to austenite reversion and subsequent transformation to untempered martensite with some retained austenite also present.

III-F-5. Grozin, B. D. and S. B. Nizhnik, "Phase and Structural Changes in Carbon Steel Under the Impulsive Action of Elevated Temperatures and Pressure," Physics of Metals and Metallography 12:73, (1961)

A metnod is used which simulates the operation of machine components in conditions of the short-time action of elevated temperatures and pressures. The method is based on the use of a pulsating flow of compressed gases at high temperatures and mkes it possible to create structural changes in the surface layers of the steel, such as actually take place in the machining of machine components and in the process of their operation. It has been found that the short-time action of elevated temperatures and pressures causes the formation of specific quenching and super-rapid tempering structures in the surface layer of the steel. The phase composition of these structures depends on the carbon content of the steel, while the depth of its distribution is determined by the initial heat treatment.

III-F-6. Kuznetsov, V. D.; K. V. Savitskiy and N. N. Sukharina, "Some Features of the Structure of the White Layers," Physics of Metals and Metallography 15:35, (1963)

Surface layers and sectors of high hardness, which are called "white" or "unetchable" layers are observed both when steel and irons are under friction and when these materials are subject to mechanical, chemico-thermal, electro-erosion and other treatments. The nature of the white layers is very far from having been revealed. Without approaching the problem of analyzing existing hypotheses, we will only note that in most cases the layers are regarded as the result of quenching under particular circumstances. When heated these layers undergo tempering, preserving rather higher hardness figures than those for normally quenched steel. The existence of different and at the same time contradictory hypotheses shows that these white layers are very different in structure, depending on the conditions under which they arose. For instance, a number of authors have found that the unetchable sectors are hard and undergo no essential changes in properties if heated above critical point.

III-F-7. Manion, S. A., and T. A. C. Stock, "Adiabatic Shear Bands in Steel," International Journal of Fracture Mechanics 6:106-1[illegible], (1970)

Bands of intense shear have been reported in steels which have been subjected to a high strain rate. It was proposed that these bands were caused by unstable adiabatic shear; that the rate of thermal softening (as heat is generated locally by plastic work) is greater than the rate of work hardening of the metal. Thus shear continues preferentially in these soft bands and, if the deformation leads to fracture, then fracture usually occurs within these bands. On metallographic examination the bands appear white when etched in picral or nital, and have always been assumed to consist of martensite. Work was undertaken to check this assumption.

III-F-8. Martin, J. A.; S. F. Borgese and A. D. Eberhardt, "Microstructural Alterations of Rolling-Bearing Steel Undergoing Cyclic Stressing," Journal of Basic Engineering 88:555-567, (September 1966)

After prolonged cyclic stressing rolling contact, AISI 52100 bearing steel parts develop extensive regions of microstructural alteration, designated as white etching areas. These are oriented in predictable directions relative to the rolling track. Lenticular carbides are always associated with these areas. Evidence is presented indicating that the boundaries of lenticular carbides constitute planes of weakness which may be preferred planes of fatigue cracking. In the transmission electron microscope, the martensitic structure appears gradually transformed into a cell-like structure by the action of cyclic stress. The size of crystallites is greatly reduced in this process. The density of microstructural change is found increased with cycling and is distributed in depth along a curve resembling that of the calculated maximum unidirectional shear stress with little or no visible change in the region of maximum orthogonal (alternating) shear stress.

III-F-9. Nizhnik, S. B. "Austenitic Transformation Mechanism under the Conditions for the Formation of 'White' Layers," Physics of Metals & Metallography, 15:71, (No. 4, 1963)

At heating rates of 10^5 - 10^4 deg/sec with external pressure, depending on the initial heat treatment of carbon and chromium steels, it has been found that either the diffusion of diffusionless austenitic transformation mechanism may prevail. It is noted that the influence of the temperature of a rapid heating and mechanism of austenitic transformation on the microstructure of the secondary quenching zone can be established by the staged etching away of the "white" layers.

III-F-10. O'Brien, John L., and Alwyn H. King, "Electron Microscopy of Stress-Induced Structural Alerations near Inclusions in Bearing Steels," ASME Trans, p. 568-572, (September 1966)

The white-etching structural alteration occurring around nonmetallic inclusions in cyclically stressed bearing steels was studied by transmission-electron microscopy. To use this method, thin foils were prepared with an edge running through the lateration. It was found that the alteration is due to the formation of 0.05- to 0.1-micron cells in ferrite. The cell formation is similar to that seen in fatigued iron except for the small cell size of the deformed steel. Evidence is also given that deformation causes breakup of the carbides produced on the tempering of steel prior to deformation.

III-F-11. Rohde, R. W., "Temperature Dependence of the Shock-Induced Reversal of Martensite to Austenite in an Iron-Nickel-Carbon Alloy," Acta Metallurgica 18:903-13, (1970)

Shock compression experiments were used to measure the temperature dependence from 25 to 390°C of the transition pressure associated with the reversal of martensite to austenite in an Fe-28.4 at % Ni-0.5 at % C alloy. The transition pressure decreases nonlinearly from 67 Kbar at 45°C to about 6 Kbar at

390°C. Above 300°C the slope of the phase line is -0.25 Kbar/°C, whereas below 250°C the slope is -0.14 Kbar/°C. These data are analyzed by two thermodynamic procedures: (1) by assuming that the reversal is an isothermal transformation and (2) by assuming that the reversal is an adiabatic transformation. The latter procedure provides the better fit to the data. Previous hydrostatic pressure measurements of the transition from 300° to 380°C are compared with the shock compression data. Although the temperature coefficients determined in the two separate experiments are the same, the transition pressure determined in the hydrostatic experiments is about 10 Kbar lower than the transition pressure determined in the shock experiments. This discrepancy is caused by a partial reversal of martensite due to the presence of shear stresses in the shock compression experiments.

III-F-12. Russell, R. J., and P. G. Winchell, "Reversal of Fe-Ni-C Martensite by Rapid Large Shear," Metallurgical Trans 3:2403-9, (September 1972)

The conditions for reversal of martensite to austenite during large and rapidly applied shear are discussed and evaluated experimentally for the shear zone neighboring a partially pierced hole. Although the large transformation strain of reverse martensite transformation could conceivably couple with the applied shear stress to provide a large energy aiding the reversal, such extensive coupling is not experimentally found to be important. Rather the important engineering quantities to consider are the chemical stability of the martensite, the strain heating of the austenite and diffusion of heat from the shear zone.

III-F-13. Winchell, P. G., "Structure and Mechanical Properties of Iron-Nickel-Carbon Martensites," Purdue University, PhD Thesis, (August 1958)

The structure and mechanical properties of iron-nickel carbon martensites containing 0.01 - 1.0% carbon were investigated. To allow measurement of the properties and structure of the martensites prior to tempering, the nickel and carbon contents were balanced to place the Ms at about -35°C. The structure of as-formed martensite is body-centered tetragonal with the axial ratio equal to 1.005 + 0.045 (%C) at all carbon levels investigated. The "extra" (0.005) carbon independent tetragonality, which disappears during aging at 100°C, can be either true tetragonality or more reasonably apparent tetragonality due to deformation faults every 40th (211)-type martensitic plane. Precipitation of carbon commences on aging even at -40°C and results in a discontinuous decrease in the axial ratio so that after tempering at 100°C for one hour, the axial ratio is 1.008 for carbon contents between 0.2 and at least as high as 0.7%. During precipitation the electrical resistivity increased and subsequently decreases. Aging is similar to the first stage of tempering in iron-carbon alloys. Potent solid-solution strengthening in as-formed martensite due to carbon, as evidenced by increasing yield stress, occurs at low carbon levels and is independent of testing temperature, suggesting that Cottrell atmosphere formation is not a hardening mechanism. Between 0.4 and 0.8% carbon, very little additional solid-solution hardening is observed. Further strengthening in this carbon range occurs during aging. The latter strengthening increased with increasing carbon content reaching about 50,000 psi at 0.8% carbon. Solid-solution hardening is thought to be due not to an increase in the strength of the atomic binding but to the elastic interaction between dislocation stress fields and stress fields around random carbon atoms. The role of tetragonality, itself, is of secondary importance. Precipitation hardening is thought to account for hardening observed during aging.

III-F-14. Wallace, W., and T. Terada, "Nature of 'White Streaks' Observed in a Nickel-Base Superalloy," Metallurgical Trans 4:2481-2483, (October 1973)

III-F-15. Wingrove, A. L., "A Note on the Structure of Adiabatic Shear Bands in Steel," Journal of the Australian Institute of Metals 16:67, (No. 1, 1971). AD 885 185

An anomalous tempering behavior has been observed in adiabatic shear bands in steel that were previously assumed to be martensite. It has been confirmed that the structure of these bands is martensite but that they contain dense tangles of dislocations. The anomalous tempering behavior is discussed in relation to carbide precipitation behavior in martensite that contains a high density of lattice defects.

G. TESTING

III-G-1. Bailey, J. A., and J. R. E. Singer, "Effect of Strain Rate and Temperature on the Resistance to Deformation of Aluminum, Two Aluminum Alloys, and Lead," Institute of Metals Journal 92:404-408, (1963-1964)

The object of the investigation was to provide stress strain data directly applicable to fabrication processes for super-purity aluminum, a Duralumin-type alloy containing 4.2% copper, a high-strength aluminum alloy containing 5.7% zinc, and high-purity lead. Testing was carried out by means of a constant-strain-rate plane-strain compression plastometer over the strain-rate range 0.4-311/sec and at temperatures up to 0.95 of the absolute solidus temperature for each material. No relation could be found between temperature and stress at a given strain, but the stress at a temperature was related to the strain rate by a power law under all conditions of testing for the metals concerned. A comparison of the results with previous work showed that the plane-strain test, operating over a wide range of strain and strain rate, gave results that differed considerably from those obtained earlier by other testing methods.

III-G-2. Baltov, A., "On the Formation of Plastic Adiabatic Bands in a Thin Tube Subjected to a Dynamic Torsion," C. R. Acad. Sc. Paris 275:291-294, (July 24, 1972). In French

III-G-3. Barron, H. G., "Stress/Strain Curves of Some Metals and Alloys," Iron & Steel Institute Journal 182:354, (1956)

Comparative tensile tests have been carried out on a number of metals and alloys at temperatures of 20°, -78°, and -196°C using strain rates of 10^{-3} and 10^{+2} in./in./sec. Stress/strain curves are presented. The strain rate and temperature have a marked effect on iron and the softer ferritic steels. In dynamic tests below a critical temperature, all the ferritic materials exhibit a type of premature failure in which the strain is entirely localized to a short neck. It is shown that this is a consequence of the adiabatic nature of this test. The variation of upper yield stress with temperature and strain rate appears to obey an activation energy relationship over part of the range of stress. Within this range the activation energy for yielding varies with the stress in the manner predicted by Cottrell and Bilby.

III-G-4. Beeuwkes, R. Jr., "High Loading Rates in Metals," Watertown Arsenal, R-64, (June 1969). AD 265 204

High loading rate effects are found to commonly occur on both low and high speed apparatus and tests. Though commonly disregarded, it is important to understand these effects as shown by examples which also indicate how low-speed tests may often be satisfactorily substituted for high-speed tests. The severity of rates, judged by materials behavior which is considered the outstanding criterion, is found to be crucially dependent on temperature.

III-G-5. Bitans, K. and Whitton, P. W., "High-Strain-Rate Investigation, with Particular Reference to Stress/Strain Characteristics," International Metallurgical Reviews 17:66-78, (1972)

III-G-6. Bitans, K. and P. W. Whitton, "Stress Strain Curves for Oxygen-Free High Conductivity Copper at Shear Strain Rates of up to 10^3 s^{-1}," Instn Mech Engrs Proc 185:1149, (1970-71)

Shear stress-shear strain curves for o. f. h. c. copper at room temperature were obtained at constant shear strain rates in the range 1 to 10^3 s^{-1} using thin-walled tubular specimens in a fly-wheel-type torsion testing machine. Results show that, for a given value of strain, the stress decreases when the rate of strain is increased. Moreover, the elastic portion of the stress-strain curve tends to disappear as the rate of strain is increased. It is postulated that these effects are due to the formation of adiabatic shear bands in the material when the given rate of strain is impressed rapidly enough. A special feature of the design of the testing machine used is the rapid application of the chosen strain rate.

III-G-7. Campbell, J. D., and A. R. Dowling, "The Behaviour of Materials Subjected to Dynamic Incremental Shear Loading," Journal of the Mechanics & Physics of Solids 18:43-63, (1970)

Some of the difficulties inherent in attempts to study the rate dependence of the mechanical properties of solids by means of longitudinal wave-propagation experiments are discussed, and it is concluded that these difficulties can be avoided by studying the propagation of a pure shear pulse applied while the material is being slowly deformed in pure shear. A new apparatus is described, in which an incremental shear stress is applied to a thin-walled tube in a time of about 30 μsec and the speed of propagation of the resulting stress wave is measured. The apparatus is also used to test short tubular specimens in pure shear by the split Hopkinson bar technique. Results of wave-propagation tests on mild steel, copper and aluminum show that the initial response is essentially elastic, and this is confirmed by results obtained in tests on short specimens of copper and aluminum. From the latter tests, incremental stress-strain curves are derived for a strain rate approaching 100 sec^{-1}, and the rate dependence of the flow stress is compared with that obtained from compression tests at constant strain rate.

III-G-8. Culver, R. S., "Torsional-Impact Apparatus," Experimental Mechanics 12:389-405, (1972)

A torsional-impact machine has been developed to investigate the dynamic behavior of metals at large strains and high strain rates. Two machines are described; the first was used to continuously monitor stress, strain profile and temperature profile during deformation; the second was designed specifically to investigate the thermal instability strain. In both machines, the use of a shear pin made independent control of the ultimate strain possible, permitting essentially constant strain rate throughout the test. Shear-strain rates of up to 2300/sec and ultimate shear strains of up to 40% were obtained on machine No. 1. Some experimental results are presented to indicate the type of data obtained and the error limits on measurements.

III-G-9. Gruntfest, I. J., "The Tensile Rupture of Hard Plastics," Journal of Polymer Science 20:491-494, (1956)

The tensile strength of polymethyl methacrylate is calculated from "modulus" data applying a criterion for mechanical stability and assuming that the failure process is adiabatic. Reasonable agreement with observed values is obtained. Application to the tensile strength of glass and of nylon is also considered.

III-G-10. Hoggatt, C. R., and R. F. Recht, "Stress-Strain Data Obtained at High Rates Using an Expanding Ring," Experimental Mechanics 9:441, (1969)

Dynamic uniaxial tensile stress-strain data are obtained at high strain rates by measuring the kinematics of thin-ring specimens expanding symmetrically by virtue of their own inertia. Impulsively loaded to produce high initial radial velocities, expanding rings are decelerated by the radial component of the hoop stresses. Differential equations of motion are evaluated experimentally to obtain the stress-strain (constitutive) relationships which govern the magnitude of these stresses. Techniques have been developed for producing symmetric radial expansion and measuring resulting displacements precisely as a function of time. Dynamic stress-strain relationships have been obtained for 6061-T6 aluminum, 1020 cold-drawn steel and 6Al-4V titanium. For each of these materials, displacement-time curves are observed to be parabolic within the resolution of the measurements. Results are presented as true-stress/true-strain relationships.

III-G-11. Hollomon, J. H., and C. Zener, "High Speed Testing of Mild Steel," ASM Trans 32:111, (1944)

Some of the difficulties encountered in high-speed testing of materials are purely mechanical, and may, therefore, be overcome with proper diligence. One difficulty, however, is associated with the unavoidable inertia of the test material itself. The intrinsic limitation which this puts upon high-speed testing is discussed. The literature is rich in data regarding the variation of the tensile properties of mild steel with rate of deformation, in the range of strain rates available with the usual testing machines. This data is so correlated that a resonable extrapolation to high strain rates may be made regarding the tensile properties. By such an extrapolation, it is predicted that in mild steel the yield strength becomes equal to the tensile strength in the range of strain rates between 1 and 10^4 sec. $^{-1}$, depending upon grain size and carbon content. The dynamic implications of an equality of the yield and tensile strengths is pointed out.

III-G-12. Hollomon, J. H., and C. Zener, "Conditions for Fracture of Steel," Metals Technology AIME 11:44, (1944)

It is commonly recognized that a given material may be described as ductile or brittle only with reference to the conditions of test. Thus under the usual test conditions, quartz is brittle, but under high pressures it is ductile. Salts that are brittle at room temperature become ductile at elevated temperatures. Pitch, brittle with respect to rapid loads, flows at low rates of loading. Pearlitic steel, ductile under the usual conditions of test, may be embrittled under the proper conditions of combined stresses, temperature, and rate of loading.

III-G-13. Johnson, W., Impact Strength of Materials, pub. by Edward Arnold Ltd., 357p. (1972)

III-G-14. Lindholm, U. S., "High Strain Rate Tests," Techniques of Metals Research, Vol. 5, Part 1, Chap. 4, edited by Dr. R. F. Bunshah, pub. by John Wiley & Sons, Inc., (1971)

III-G-15. Luerssen, G. V., and O. V. Greene, "The Torsion Impact Test," American Society for Testing Materials Proceedings 33:315, (1933)

This paper points out the need for a reliable method of determining impact resistance on very hard materials such as hardened tool steel. It reviews briefly the work of previous investigators in this field, and comments on the inadequacy of present impact methods when applied to these materials. A machine and method especially adapted to hard materials, in which the specimen is fractured torsionally under impact, are described in detail. Calibration of the machine, design of the test specimen, effect of velocity, and reproducibility of results are then discussed, and comparisons are drawn with current methods of test on softer materials. Test data are shown on three hardened tool steels drawn over a range of hardness. These are discussed briefly, and general conclusions are drawn on the practical value of such data and the utility of the machine as a control and research instrument.

III-G-16. Manion, S. A., and T. A. C. Stock, "The Measurement of Strain in Adiabatic Shear Bands," Journal of the Australian Institute of Metals 14:190-197, (1969) III-G-17. McCaughey, J. M., and M. A. Dragoo, "High Speed Compression Tests of Projectile Steels," Frankford Arsenal, R-798, (May 1947). AD 493 311

The stress-strain relation for adiabatic deformation is extremely important because it is probable that the phenomenon of shatter failure results essentially from the instability of adiabatic deformation of the shot during penetration. To supplement the information obtained with quasi-static compression tests, adiabatic tests were conducted. While static compression tests are a convenient way of studying the effects of steel composition and heat treatment on some of the mechanical properties important to shot performance, there are certain aspects of shot steel behavior in compression on which it gives no information.

III-G-18. Read, T. A., H. Markus, and J. M. McCaughey, "Plastic Flow and Rupture of Steel at High Hardness Levels," Fracturing of Metals, pub. by American Society for Metals, (1948); also in ASM Trans 40B:228-243, (1948)

Stress-strain relations for a medium carbon steel were measured over a range of hardness levels from Rockwell C-40 to 66. The data indicate that stress increases as the nth power of the strain for strains greater than 0.04. The strain hardening exponent n so determined has a minimum value when specimens of these steels are tempered in the neighborhood of 500°F. It is suggested that the low values of energy absorption in the torsion-impact and notched-bar bend tests for heat treated medium and high-carbon steel specimens tempered near 500 F may result from the low value of the strain-hardening exponent obtained after this tempering treatment.

III-G-19. Zener, C., and J. H. Hollomon, "Effect of Strain Rate upon Plastic Flow of Steel," Journal of Applied Physics 15:22, (1944)

An experiment was designed to check a previously proposed equivalence of the effects of changes in strain rate and in temperature upon the stress-strain relation in metals. It is found that this equivalence is valid for the typical steels investigated. The behavior of these steels at very high rates of deformation may, therefore, be obtained by tests at moderate rates of deformation performed at low temperatures. The results of such tests are described. Aside from changing the isothermal stress-strain relation, an increase of strain rate tends to change the conditions from isothermal to adiabatic. It is found that at low temperatures, the adiabatic stress strain relation in the plastic range is radically different from the isothermal, having an initial negative rather than a positive slope. This initial negative slope renders unstable homogeneous plastic deformation.

IV. MISCELLANEOUS

A. REVIEWS

IV-A-1. Rogers, H. C., "Adiabatic Shearing; A Review," Drexel University, 73p., (May 1974)

Adiabatic plastic deformation is reviewed in its broadest sense with the emphasis on adiabatic shearing. The observations of this phenomenon in high speed machining and metal forming, ballistic impact, explosive fragmentation, high velocity punching, cryogenic deformation, bearing technology and several other areas are discussed at length. Also described are the material dependent aspects of adiabatic shearing. Included are polymeric materials in addition to both ferrous and non-ferrous materials. Several different analytical models of plastic instability resulting from the adiabatic shearing are presented and the merits of each compared. Since the adiabatic shearing process frequently culminates in fracture, this topic is covered extensively. A possible alternative mechanism for the formation of "knobbly" fracture surfaces is proposed. The effect of deformation in the promotion of carbide dissolution during the adiabatic deformation of steel is considered. Finally, the structure and high hardness of the "white streaks" observed in steels as a result of adiabatic shearing are discussed with respect to their interrelationship and also relative to the possible mechanisms of formation of this structure.

B. SEISMIC FAULTING

IV-B-1. Orowan, E., "Mechanism of Seismic Faulting," Rock Deformation Symposium, edited by David Griggs, pub. by Geological Society of American, p. 323, (1960)

According to the classical theory, earthquakes would be caused by fracture, or the release of static friction, followed by sliding between the fault walls and a consequent drop of stress around the fault. At a depth of 600-700 km, where the pressure is about 200,000 bars, the lowest possible estimate of the coefficient of friction (about 1) would demand principal stress differences of the order of 400,000 bars for overcoming the friction of the fault wall and producing a drop in seismic stress. Such high stresses cannot be assumed to exist, if only because the yield stress of the asthenospheric rocks can hardly have an order of magnitude exceeding a few tens or at most hundreds of bars. This estimate is obtained by extrapolation of the observed creep behavior of hard materials with the assumption that the effect of a hydrostatic pressure is similar to that of a correspondingly increased molecular cohesive pressure; its order of magnitude agrees with that of the stress drop estimated from the energies released in earthquakes. A detailed discussion of this difficulty shows that earthquakes, except at focal depths less than about 5-10 km, cannot arise in the manner implied in the classical theory. The only plausible alternative available at present is that they are due to an instability of plastic deformation (creep) such as gives rise to slip bands, Luders bands, the Hanson-Wheeler creep deformation bands, and many other similar phenomena. If creep produces structural changes that accelerate further creep, the deformation concentrates gradually into thin layers in which high

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flow rates can develop, and finally even shear melting may occur by heat development due to plastic deformation. Such a mechanism would explain the sequence structure of earthquakes (fore and after-shocks). If fracture and frictional sliding are impossible and faulting can occur only by the gradual concentration of creep deformation into thin zones, the stress concentration around the edges of a fault cannot propagate this fault immediately over the entire stressed volume, as would be the case with faulting due to fracture. The fault can extend only after the occurrence of a certain amount of creep leading to progressive strain concentration in the region put under increased stress by the preceding faulting.

C. SPALLATION OF HAMMER

IV-C-1. McIntire, H. O., and G. K. Manning, "Producing Martensite by Impact," Metal Progress 74:94, (1958)

IV-C-2. McIntire, H. O., and G. K. Manning, "Spalling of Hand Hammers," National Safety News, (No. 10, 1958)